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ABSTRACT

A design analysis of a submarine's pressure hull components, fabricated from HY-130 steel, is performed in order to determine the welding requirements for fabrication. The amount of welding required is expressed in both linear feet and weight of weld metal deposited.

Data on experimental welding of HY-130 is presented. The experiments consisted of single and double pass laser welding of restrained butt welds in one inch thick plates. Penetration capabilities obtainable with 12 KW of laser beam power were determined. Temperature distributions, longitudinal strains, and transverse strains experienced during laser welding of the HY-130 plates are presented in graphical and tabular form.

An economic analysis, comparing shielded metal arc, gas metal arc, laser, and electron beam welding processes, for fabricating the HY-130 pressure hull is performed. The economic factors considered were labor and overhead costs, filler metal costs, shielding gas costs, and electrical power consumption.

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AN ECONOMIC AND TECHNICAL STUDY ON THE FEASIBILITY
OF USING ADVANCED JOINING TECHNIQUES IN CONSTRUCTING
CRITICAL NAVAL MARINE STRUCTURES

by

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B.S., A.A., Miami (Ohio) University
(1973)

Submitted in partial fulfillment
of the requirements for the
degree of
OCEAN ENGINEER
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MASTER OF SCIENCE IN NAVAL ARCHITECTURE
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L.T. WAYNE JOSEPH ROGALSKI

Submitted to the Department of Ocean Engineering on May 11, 1979
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Engineer, and for the Degree of Master of Science in Naval Architecture
and Marine Engineering.

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CHAPTER I

INTRODUCTION

A. Background

Joining techniques can be traced back to prehistoric days. Copper-gold and lead-tin alloys were used for soldering prior to 3000 B.C. [1]. Evidence exists that iron and steel were welded into composite tools and weapons as early as 1000 B.C. However, the relatively low temperature heat sources available at that time severely limited welding applications [2].

Modern welding technology really began with the advent of readily available electric power towards the end of the 19th century. Table I, based on data presented by Masubuchi [3], summarizes the important discoveries in joining techniques and their applications since the 1890's. Today, there are approximately 50 welding processes in use [1, 4]. Of particular importance was the effect that World War II had on welding use. The demand for greater numbers of ships greatly accelerated the use of welding. Through the application of welding technology, the United States was able to build approximately 4,700 ships [5]. This accelerated use of welding was not without risk, however. In the years following the war, a significant number of welded ships experienced structural failures. Of the almost 5,000 ships built, twenty either broke in two or had to be abandoned due to excessive structural damage [6]. These events ultimately led to improvements in welding techniques through the understanding of brittle fracture.

Table IHistorical View of Welding Developments

<u>Time Frame</u>	<u>Development</u>
1890	The first U.S. metal-arc welding patent issued to Charles Coffin (1889).
1910-1920	Introduction of covered electrodes by K Jelborg in Sweden (1912). First use of metal-arc welding in shipbuilding (repair work during World War I).
1920-1930	The first all-welded ship built in England (Fullage, 1921).
1930-1940	First patent for inert-gas electric-arc welding was issued to Hobart and Devers. Submerged arc welding development in U.S.
1940-1950	Demands of World War II accelerate the use of metal-arc welding in shipbuilding. Development of gas tungsten-arc welding. Development of gas metal-arc welding.
1950-1960	Electroslag welding introduced in Russia. Introduction of CO ₂ shielded metal-arc welding. Development of new processes, electron-beam, ultrasonic, and laser.
1960	Introduction of Battelle Narrow-Gap Process.
1968	Use of various processes in shipbuilding: Covered electrodes 80-90% Submerged arc 10-15% CO ₂ shielded 1% Others .1%

B. Trends in the Adoption of Advanced Welding Processes

An interesting aspect of Table I is the data presented on welding processes used in shipbuilding as of 1968-1969. Although significant progress had been made in the development of welding techniques, corresponding advancement in shipbuilding applications of the new techniques was not as substantial as might have been expected. As of 1969, approximately 80-90% of ship hull joints (in length) were still being welded manually, using covered electrodes [1, 3]. This process was developed more than sixty years ago. Although the submerged-arc process accounted for 10-15%, it too was developed over forty years ago. Very limited use was being made of more advanced techniques.

In many respects, the long lead time in implementing new welding techniques is based on sound reasoning. An urgent need, such as that experienced during World War II, is not always available to accelerate the acceptance of new technology. The structural design of ship hulls also present a problem. A large percentage of the joints are fillet welds which are periodically interrupted by intercoastal structural members. This makes it difficult to apply automatic welding processes. In addition, the quality of welding as practiced has improved greatly over the years. Substantial economic outlays for equipment and personnel training have already been invested, resulting in a sense of security in the use of more established joining methods. This motivation is clear when one considers the worth of modern ships. The cost of our new Trident submarines may exceed a billion dollars each [7]. A reluctance to use new technology vice more proven welding methods on such a costly item would be understandable. The Alaskan pipeline serves as another example.

Although more modern joining procedures could have been employed, the desire to minimize risk resulted in the extensive use of covered electrodes.

Notwithstanding the remarks made in the previous paragraph, it is unrealistic to assume that in future years shipbuilding will be relying solely on the same joining processes now utilized. First of all, the structural design of ships may change. Ships hulls have for years been designed based on rules developed through experience, such as those of the American Bureau of Shipping (ABS). ABS standards now incorporate the ability for designers to depart from the rules [8]. Justification and proof of design adequacy must of course be provided by the designer. Significant changes in structural design could be accompanied by an increased attractiveness of previously unused welding techniques. The future use of higher strength steels, or aluminum and titanium alloys may necessitate new methods of fabrication.

Impetus towards implimenting more modern welding techniques may be provided by other than purely engineering concerns. Economic considerations play a powerful role in the design and construction of ships. The ship building industry is continuing to seek out ways of increasing the speed of the welding process [9]. Increased welding speeds and deposition rates can correlate to increased productivity, and lowering of production costs. Wages have greatly increased over the years. The replacement of labor intensive welding processes with automated techniques could also provide for reductions in fabrication costs. One important aspect of laser and electron-beam welding processes is their ability to weld without the use of filler metals. This represents a savings in metal

resources and their associated costs. A strong desire for energy conservation will provide additional motivation towards changes. The ever increasing expense of electrical power will benefit those welding processes with the greatest overall efficiency.

C. Aim and Purpose of Study

The primary purpose of this thesis is to investigate the potential for utilizing advanced welding processes in the fabrication of submarines. The structural material chosen for the submarine is Hy-130, a high strength quenched and tempered steel. The Hy-130 welding capabilities of gas metal arc (GMA), shielded metal arc (SMA), electron-beam (EB), and laser welding are to be considered. Economic comparisons between the four processes will also be made.

Research is currently being conducted at M.I.T. to develop multi-dimensional programs capable of accurately predicting temperature distributions, as well as thermal stresses and metal movement, during the welding of thick sections [10]. The ultimate goal is to predict distortion and residual stresses, and thus avoid problems in the later stages of the fabrication process. In contrast to the effort necessary to experimentally measure distortion and residual stresses, computer analysis would provide for a significant savings in cost, manpower, and time.

The development, and assessment of capabilities, of a computer program requires the existence of a data base on which to compare known results with those predicted by the program. The existence of experimental data on transient thermal strains in thick Hy-130 plates is limited. Recent experimental work on gas metal arc welding of thick Hy-130 plates has been

accomplished by Lipsey [11]. Similar work by Conneybear [12], using electron-beam welding, added to the accumulation of data. In support of the computer program development and the need for experimental data, this study will also undertake the task of measuring the temperature distribution and transient thermal strains encountered during laser welding of thick Hy-130 plates.

In summary, this thesis will undertake to accomplish the following:

1. To determine the welding requirements anticipated in the construction of a Hy-130 submarine. Structural design of primary pressure hull components will reveal scantlings and amount of welding to be encountered.
2. To determine laser capabilities for welding thick Hy-130 plates.
3. To measure temperature distributions and transient thermal strains encountered during laser welding.
- 4. To perform a cost analysis, comparing GMA, EB, SMA, and laser welding processes in the fabrication of the Hy-130 submarine.
5. Upon completion of the computer program development, and with time permitting, determine the applicability of the multi-dimensional program to laser welding of thick sections.

CHAPTER II

MATERIAL CHARACTERISTICS OF Hy-130

In order to increase the operating depth capabilities of submarines, materials with higher strength-to-weight ratios are needed. Hy-80 steel, first introduced in 1958, has a yield strength of 80,000 psi. Today, Hy-80 is still the basic steel used for submarine hulls. Hy-100, a steel very similar to Hy-80, is also used to a limited extent. A high strength quenched and tempered steel developed for the Navy, and designated Hy-130, is expected to be used for future submarines.

Hy-130 was initially designated Hy-140, but was renamed when it was found that only 130,000 psi yield strength could be guaranteed in the welds. In 1969, the Lockheed Missile and Space Company built the first deep submergence rescue vehicle (DSRV) using Hy-130. The DSRV is capable of diving to a depth of 6,000 feet. In addition to the high strength characteristics of Hy-130, the steel also exhibits good fracture toughness at low temperatures [14]. The chemical composition of Hy-130 quenched and tempered steel is presented in Table II. The mechanical properties of Hy-130 in the "as received" condition are presented in Table III.

In order to utilize finite element programs for predicting heat flow and thermal strains which occur during welding, the physical and mechanical properties as functions of temperature, from room temperature through the melting point, must be known for the material being evaluated. Schrodtt [13] developed curves for the physical and mechanical properties of Hy-130 as functions of temperature. His data was derived from references [16-25]. These curves are currently the most valid

approximations available for Hy-130 properties at elevated temperatures. The mechanical and physical properties of Hy-130 as functions of temperature are presented in Figures 1-10. Summaries of these properties are also presented in Tables IV and V.

Table IIChemical Composition of Hy-130

<u>Element</u>	<u>Weight Percent</u>
Ni	4.75 - 5.25
Cr	0.40 - 0.70
Mn	0.60 - 0.90
Si	0.20 - 0.35
Mo	0.30 - 0.65
V	0.05 - 0.10
C	0.08 - 0.12
P	0.010 maximum
S	0.015 maximum
Ti	0.02 maximum
Cu	0.25 maximum
Fe	Remainder

Table IIIMechanical Properties of Hy-130

Yield stress	145 ksi
Tensile stress	147 ksi
Elongation in 2 inches	20%
Reduction of area	69%
V-notch requirements	60 ft-lbs at 70°F and 0°F

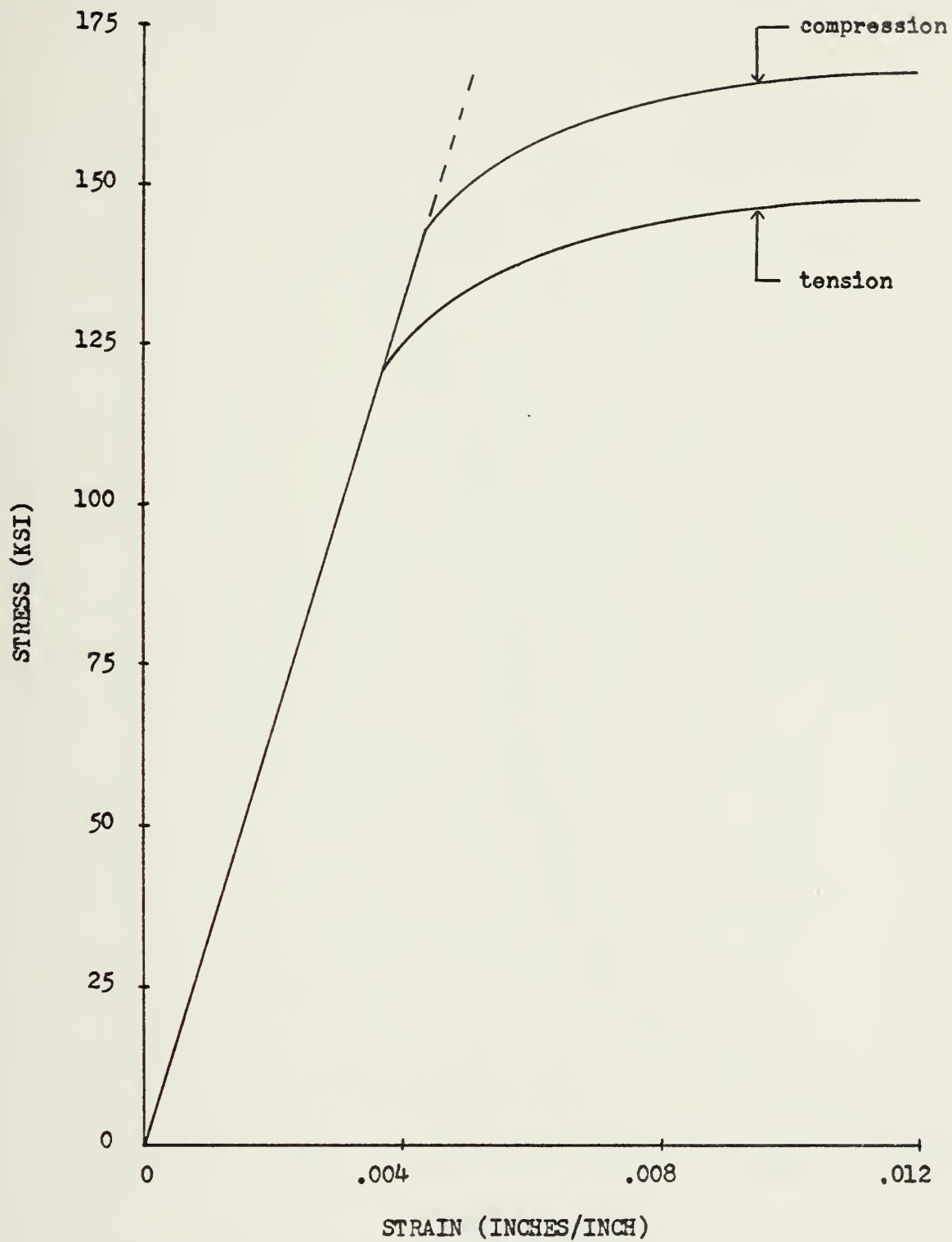


Figure 1- TYPICAL STRESS STRAIN DIAGRAM FOR HY-130

AT ROOM TEMPERATURE

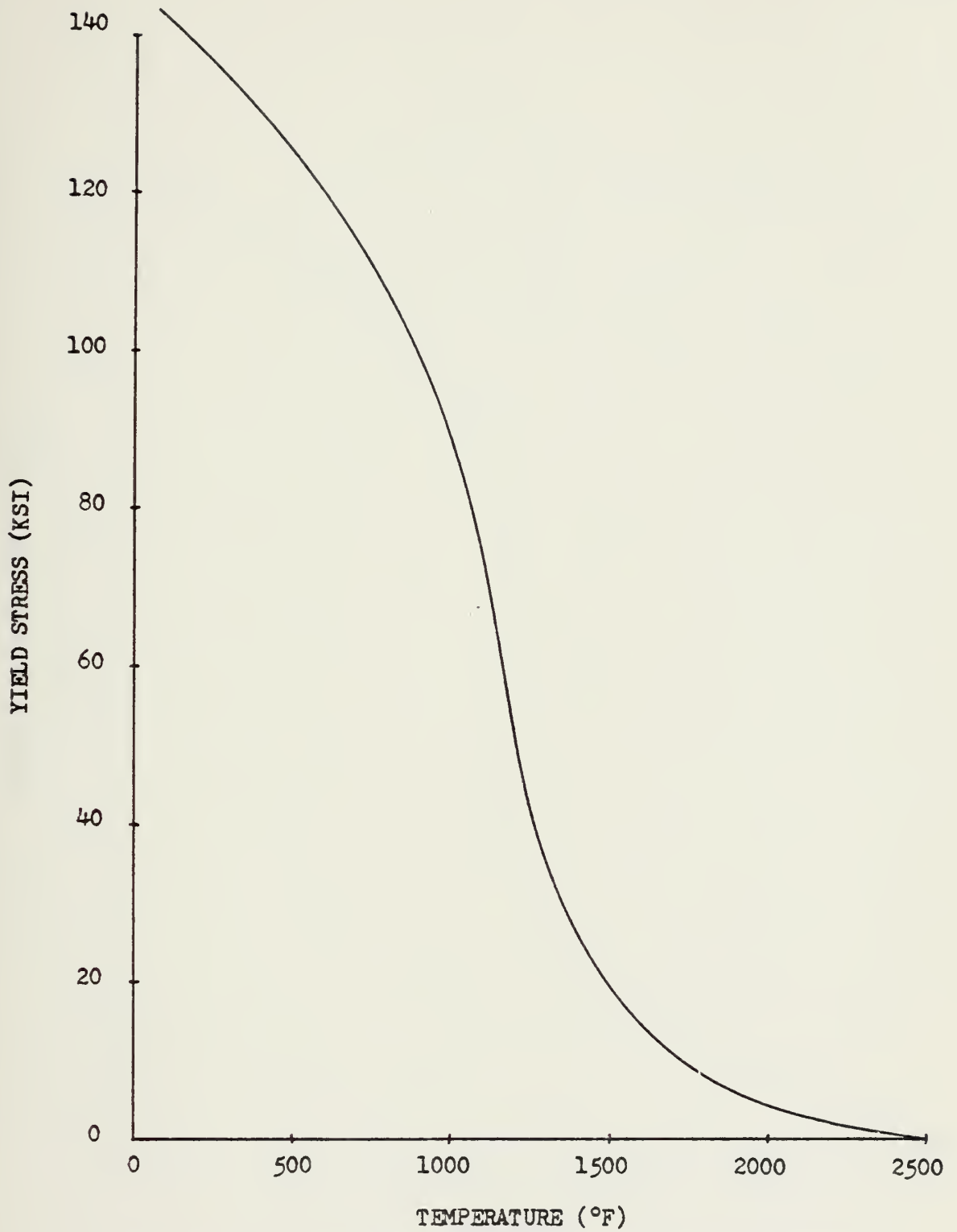


Figure 2- ESTIMATED EFFECT OF TEMPERATURE ON 0.2% OFFSET
YIELD STRESS FOR HY-130

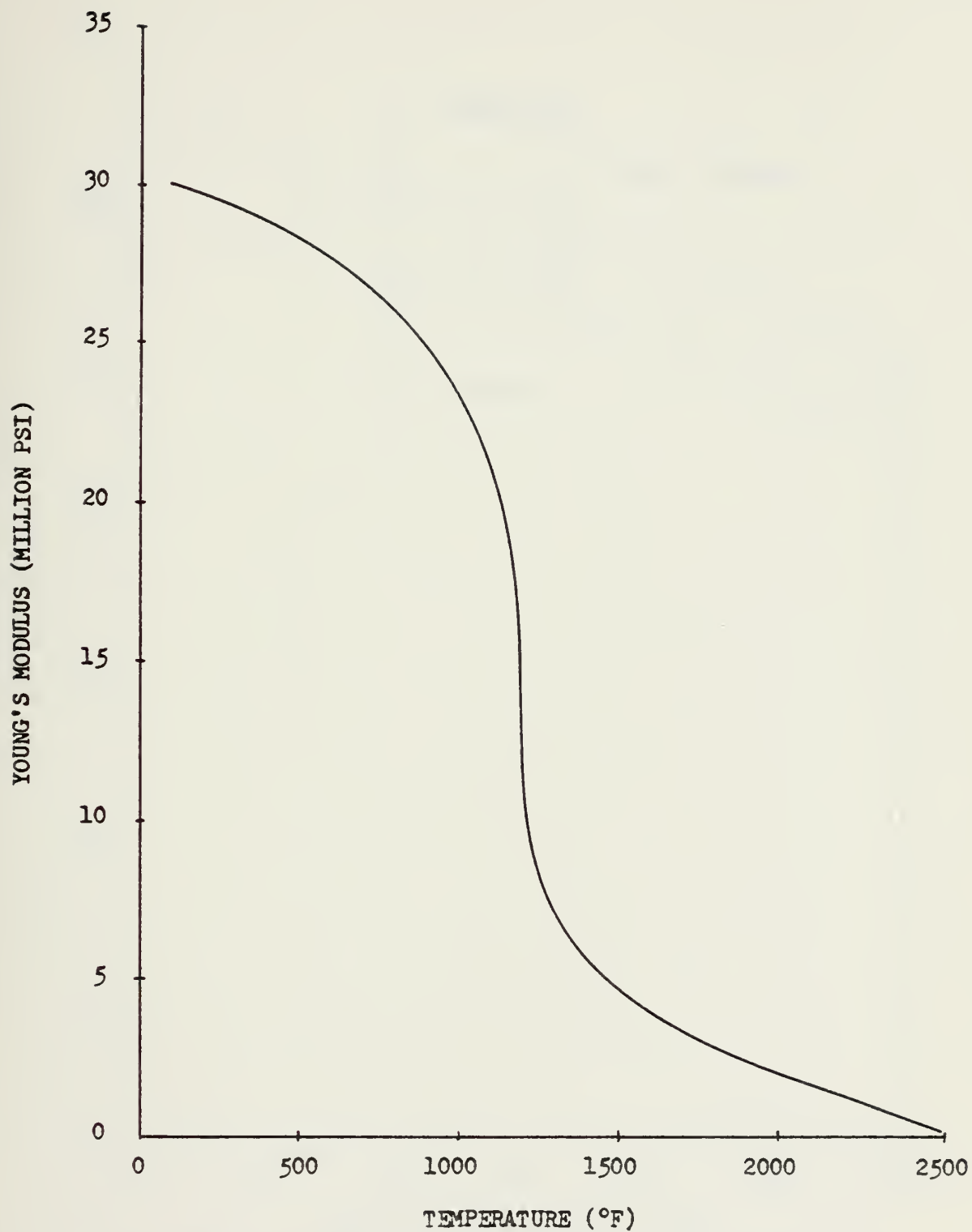


Figure 3- ESTIMATED EFFECT OF TEMPERATURE ON YOUNG'S
MODULUS FOR HY-130

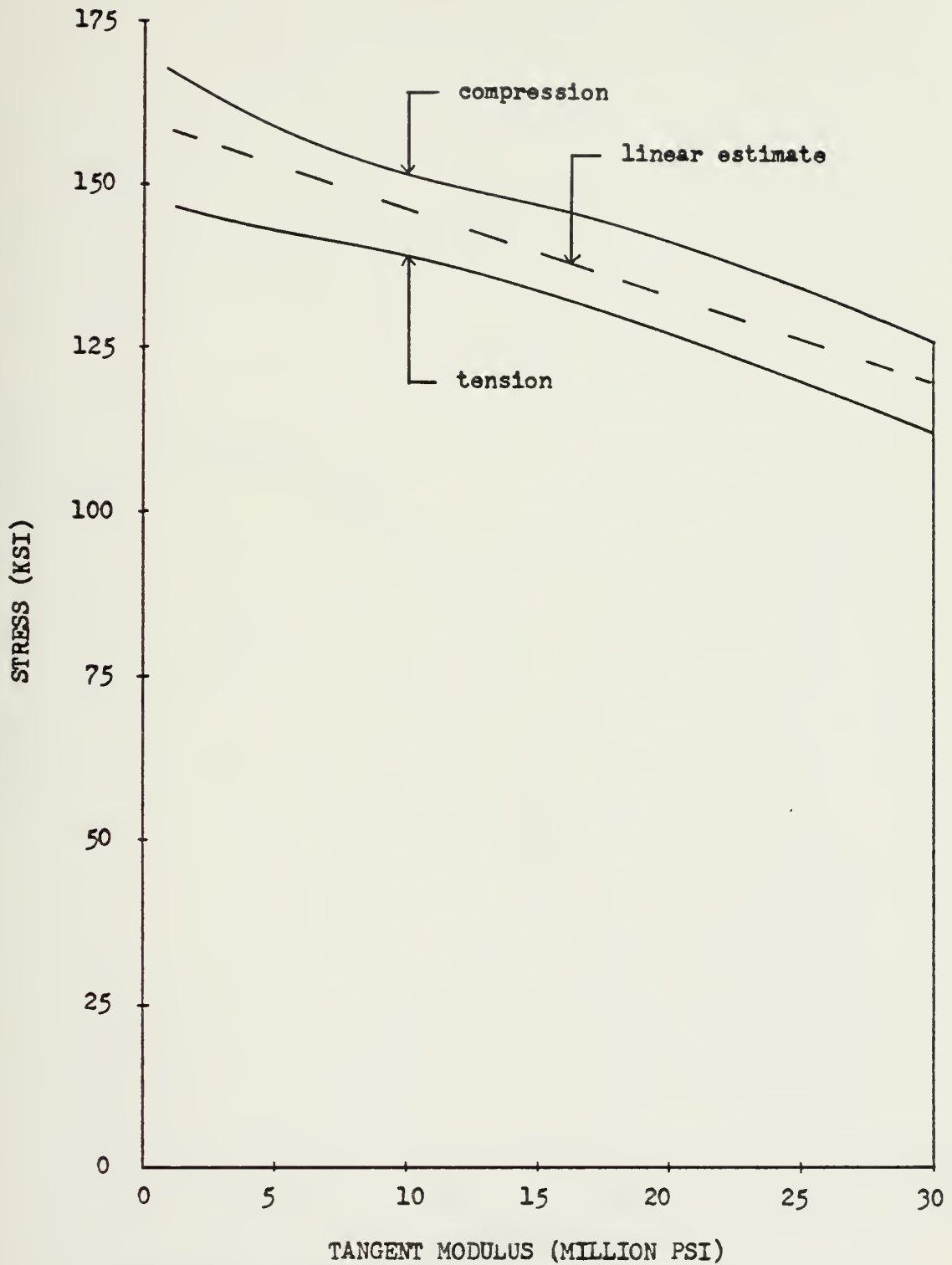


Figure 4- TANGENT MODULUS FOR HY-130

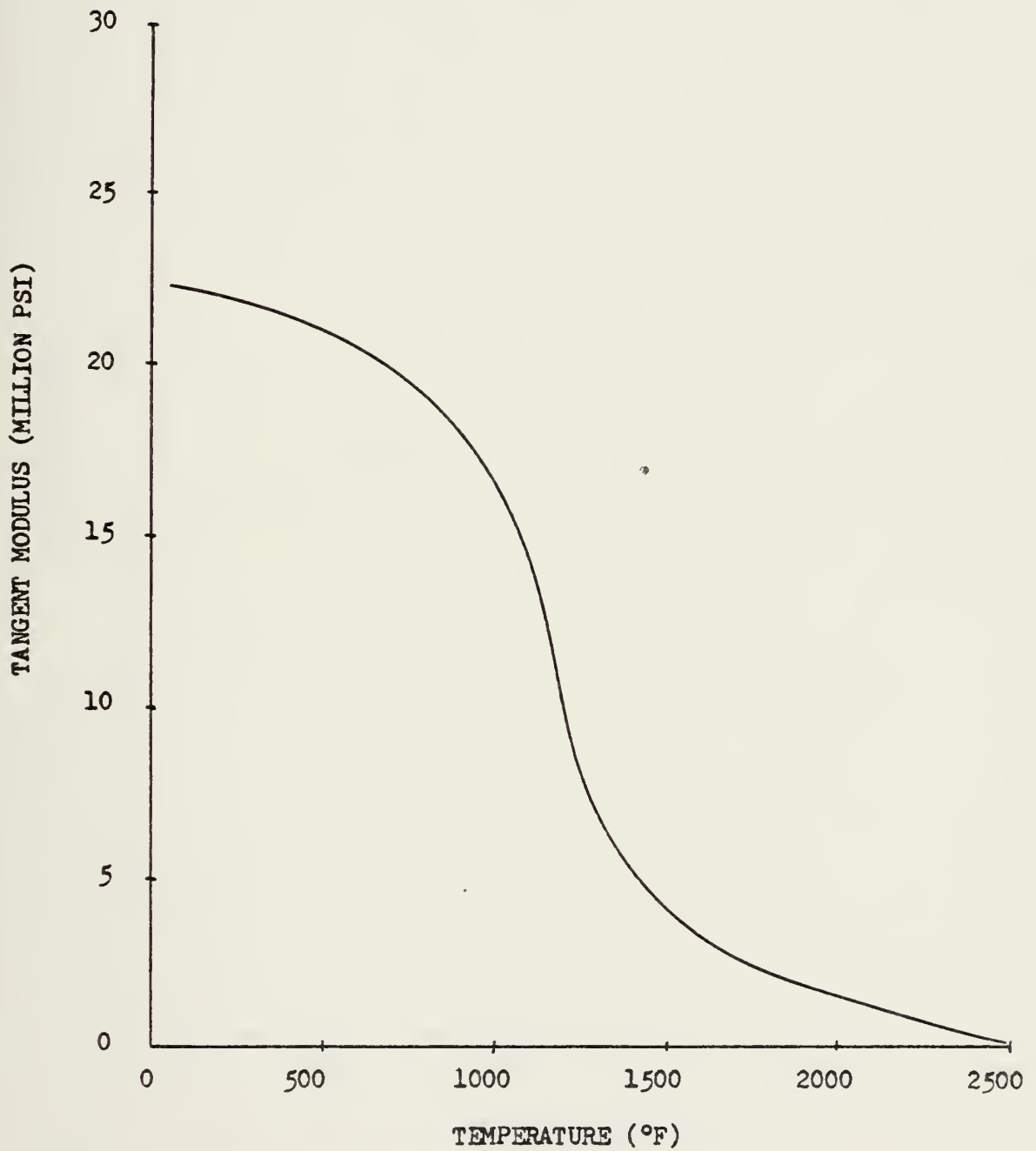


Figure 5- ESTIMATED EFFECT OF TEMPERATURE ON TANGENT
MODULUS FOR HY-130

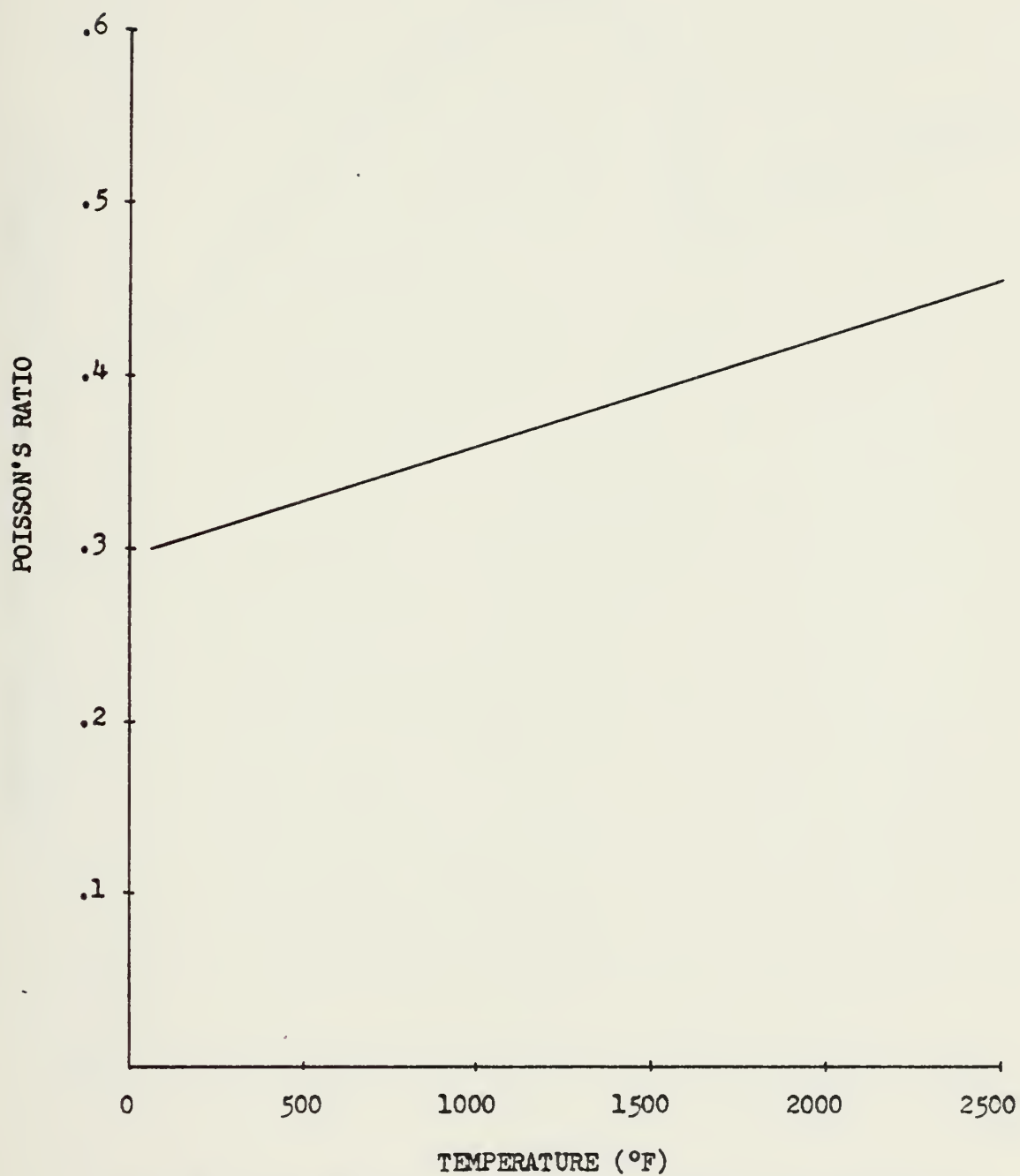


Figure 6- ESTIMATED EFFECT OF TEMPERATURE ON POISSON'S
RATIO FOR HY-130

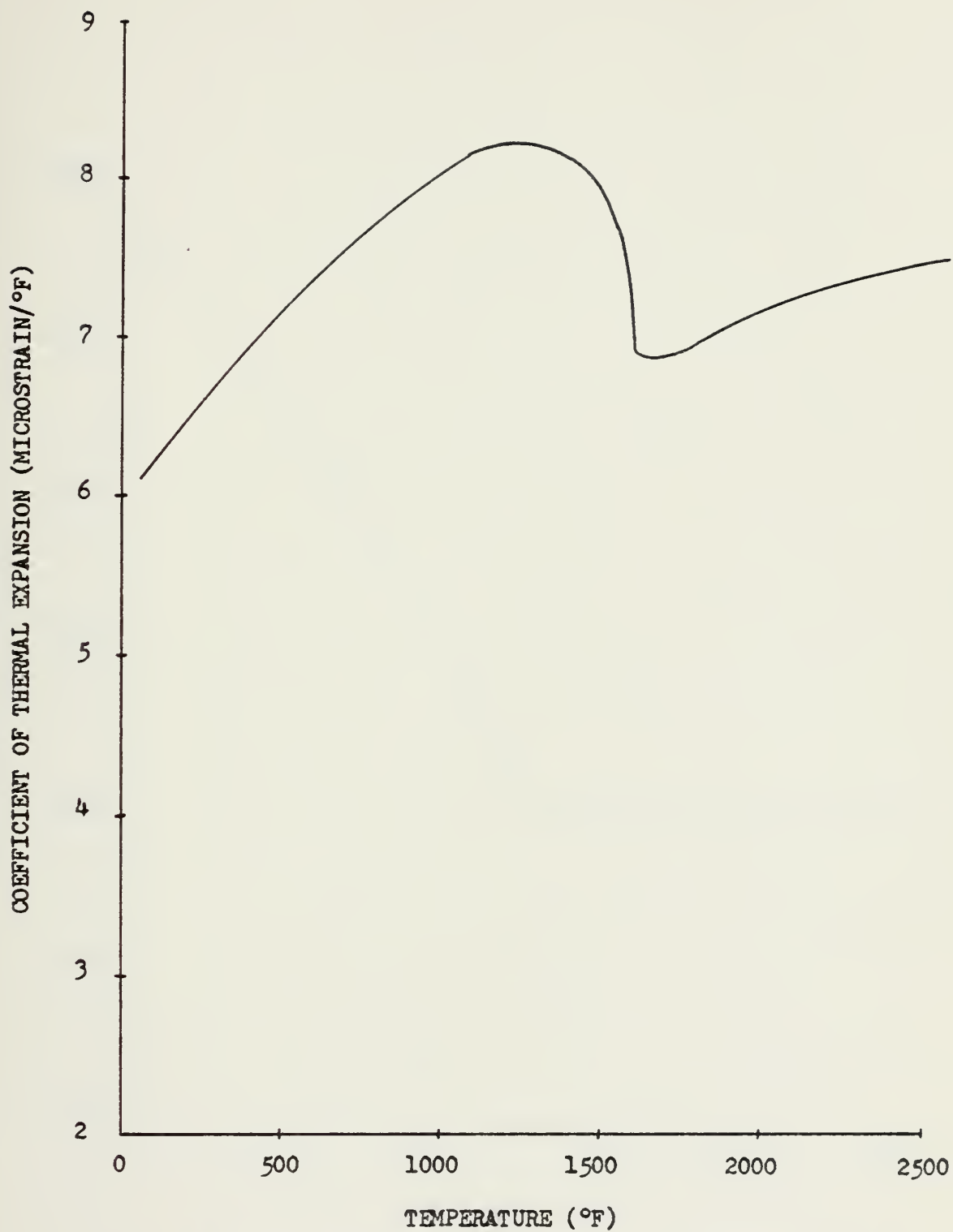


Figure 7- ESTIMATED EFFECT OF TEMPERATURE ON COEFFICIENT OF
THERMAL EXPANSION FOR HY-130

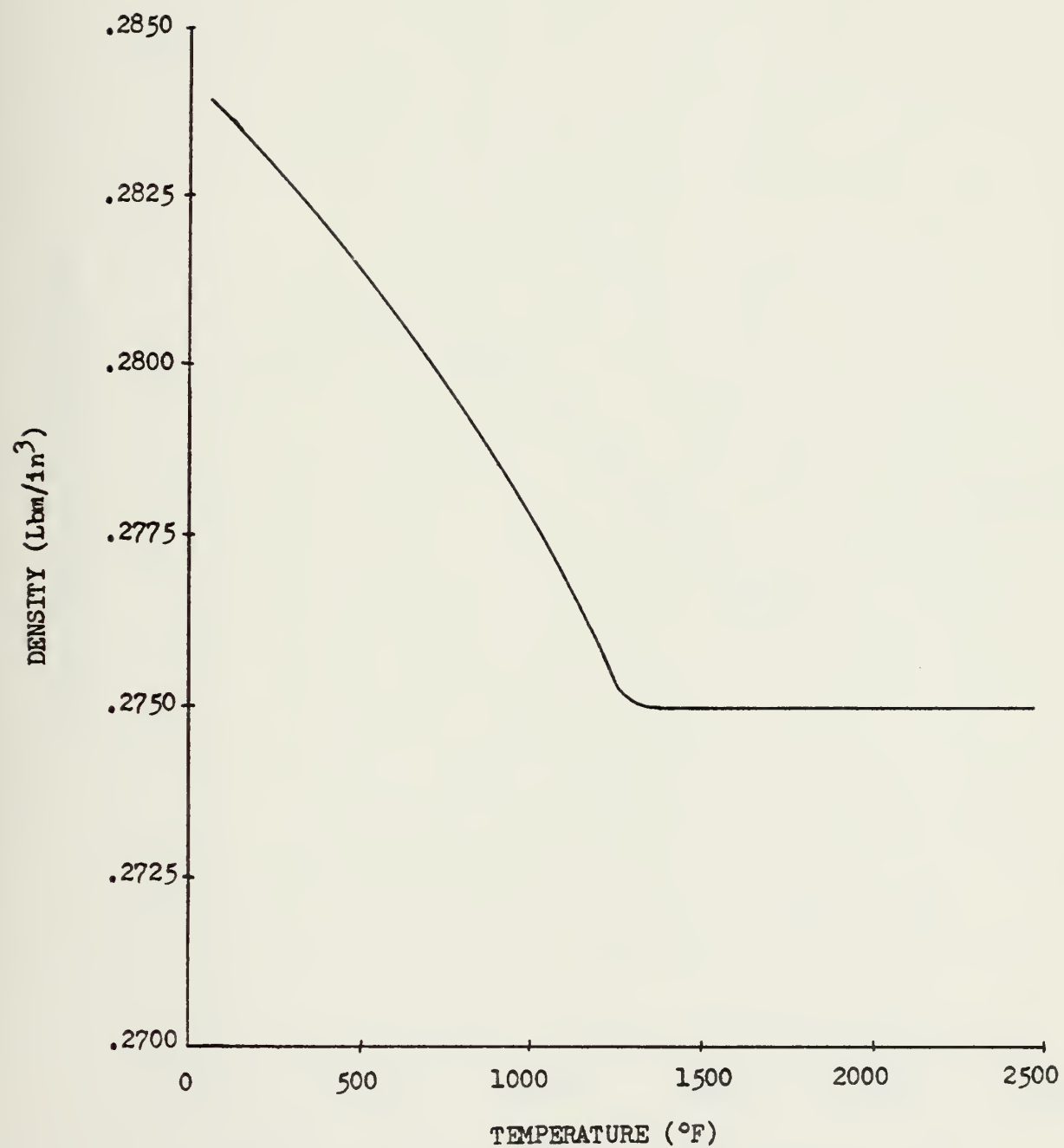


Figure 8- ESTIMATED EFFECT OF TEMPERATURE ON DENSITY
FOR HY-130

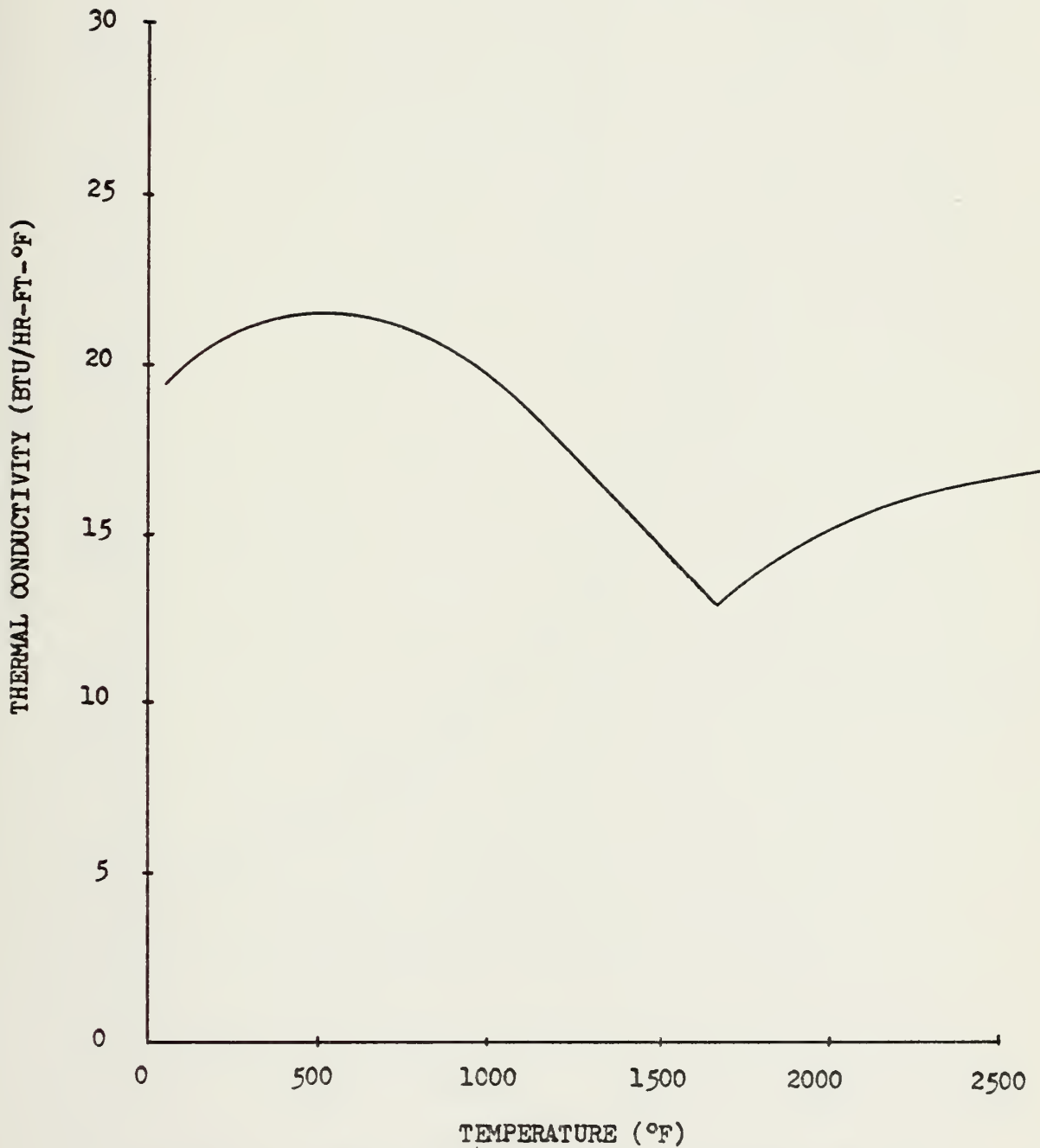


Figure 9- ESTIMATED EFFECT OF TEMPERATURE ON THERMAL
CONDUCTIVITY OF HY-130

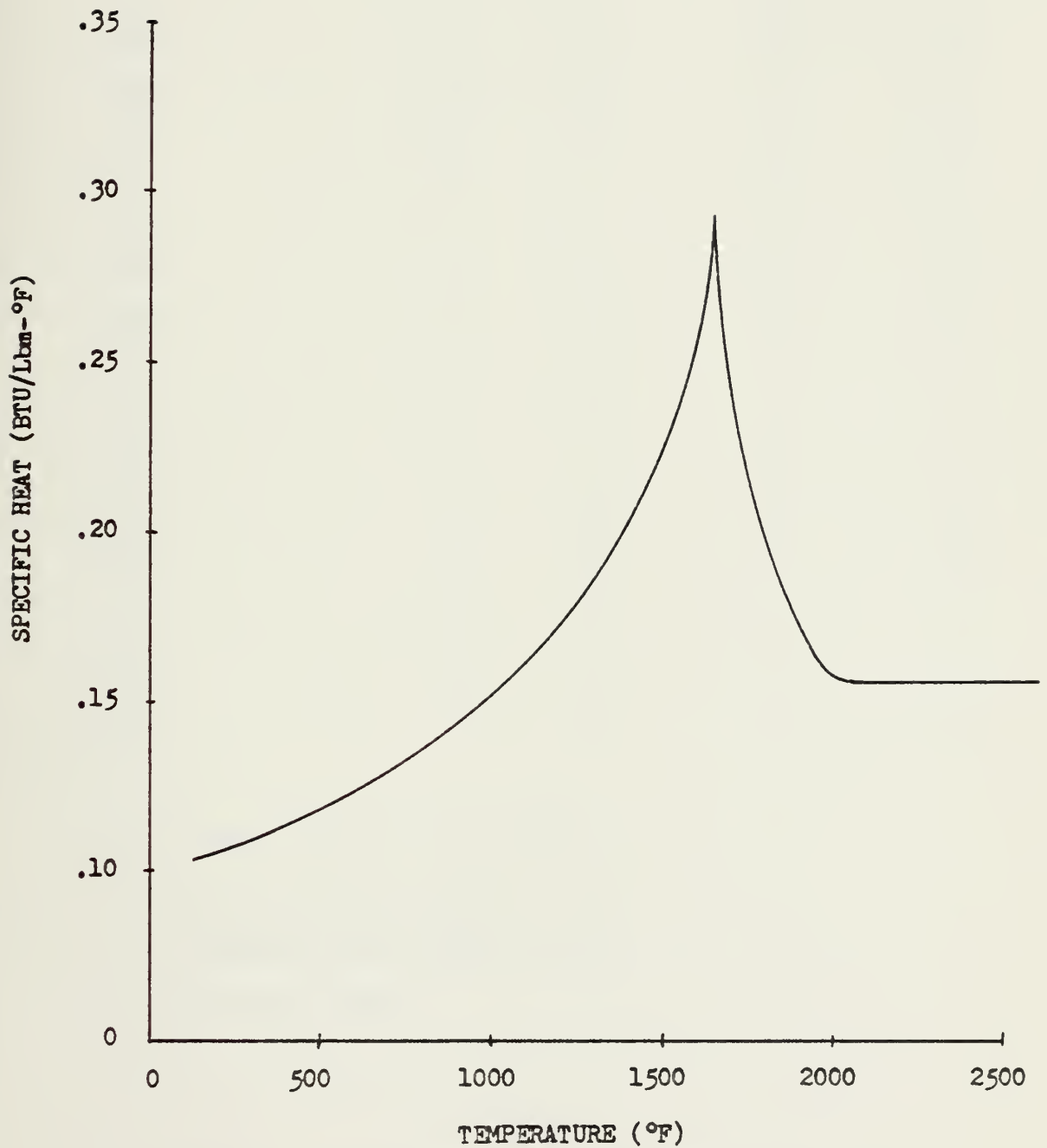


Figure 10- ESTIMATED EFFECT OF TEMPERATURE ON SPECIFIC
HEAT OF HY-130

Table IVSummary of Mechanical Properties for Hy-130

<u>Temperature (°F)</u>	<u>σ</u>	<u>E</u>	<u>H</u>	<u>ν</u>
68	143	30	22.2	.30
200	138	29.6	21.8	.308
400	131.5	28.8	21.2	.321
600	122	27.7	20.5	.334
800	110	26	19.2	.346
1000	88	22.7	17.0	.359
1200	50	14.0	9.2	.372
1400	25.5	5.0	4.9	.384
1600	11.2	4.0	3.1	.397
1800	6.0	3.0	2.2	.410
2000	4.0	2.0	1.5	.422
2200	2.0	1.2	.8	.435
2400	1.0	.4	.4	.447
2500	0	0	0	.454

σ = yield stress 2% offset (Ksi)

E = Elastic Modulus (million psi)

H = Tangent Modulus (million psi)

ν = Poisson's Ratio

Table VSummary of Physical Properties for Hy-130

<u>Temperature (°F)</u>	<u>ρ</u>	<u>γ_T</u>	<u>C</u>	<u>κ</u>
68	.284	6.1	19.4	.107
200	2.83	6.5	20.4	.11
400	.282	6.95	21.5	.118
600	.280	7.3	21.8	.126
800	.279	7.7	21.2	.136
1000	.278	8.0	19.5	.148
1200	.276	8.3	17.1	.168
1400	.275	8.18	15.0	.197
1600	.275	7.05	13.4	.255
1660	.275	6.92	13.1	.293
1800	.275	7.0	14.0	.18
2000	.275	7.2	15.0	.158
2200	.275	7.3	16.0	.158
2400	.275	7.4	16.7	.158
2600	.275	7.5	17.0	.158
2800	.275	7.5	7.0	.18

ρ = Density (Lbm/in³)

γ_T = Coefficient of Thermal Expansion ($\mu\epsilon/^\circ\text{F}$)

C = Thermal Conductivity (BTU/HR-ft-°F)

κ = Specific Heat (BTU/Lbm-°F)

CHAPTER III

Hy-130 SUBMARINE DESIGN

A. Design Requirements

In order to make an economic comparison of the various welding techniques that could be used in the fabrication of Hy-130 submarines, it is necessary to determine the joint types and amount of welding to be encountered. Once the welding requirements are known, the ability of the various welding processes to meet these requirements can be judged. Acceptable welding processes can then be analyzed to determine their economic and technical impacts on the fabrication process.

Modern submarines are large warships. The largest submarines currently in the fleet are 425 feet long and displace over 8,200 tons. When the Trident submarines enter the fleet, they will measure 560 feet in length and displace approximately 18,700 tons [26].

Submarines are presently fabricated from Hy-80 steel. Therefore, one is not able to refer to existing blueprints and drawings for the precise welding requirements anticipated in the construction of Hy-130 submarines. However, using the design practices outlined in references [27, 28, 29], this author adequately defined the major structural components of a Hy-130 submarine. The submarine considered in this study is as shown in Figure 11. The submarine's dimensions approximate those of a candidate submarine which was considered as a possible alternative to the very large Trident [30]. The design requirements this author imposed on the submarine are listed in Table VI.

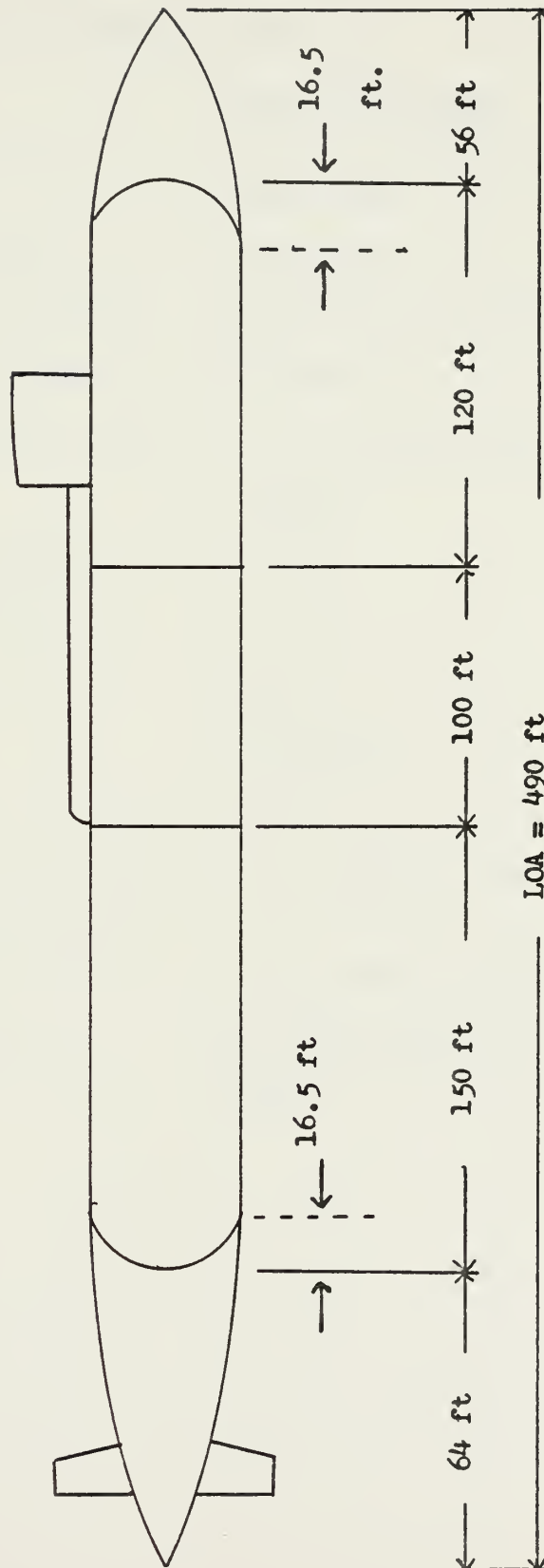


Figure 11- PROFILE OF HY-130 SUBMARINE

Table VIHy-130 Submarine Design Data

<u>Item</u>	<u>Design Requirement</u>
pressure hull diameter	33 feet (typical of modern nuclear submarines)
type of pressure hull	cylindrical
pressure hull end closures	hemispherical, 16.5 ft. radius
submarine operating depth	1000 feet
collapse depth safety factor	1.5 x operating depth
collapse depth	1500 feet
sea pressure at 1000 feet	444 psi
sea pressure at 1500 feet	666 psi
structural material	Hy-130
yield strength	130,000 psi
Poisson's ratio	.3
Shell buckling safety factor	2.25 x operating depth
General instability safety factor	3.75 x operating depth
corrosion allowance	1/8 inch on shell 1/6 inch on each side of external frames

B. Pressure Hull Calculations

A cylindrical pressure hull is most often selected for submarine application. A cylinder allows for much easier arrangement of equipment, and except for a sphere, is the strongest and lightest structure for resisting external sea pressure. The two main stresses in the pressure hull are circumferential (tangential) stress, and longitudinal (axial) stress. Equations (1) and (2) provide good estimates of these stresses.

Circumferential stress: σ_{θ}

$$\sigma_{\theta} = \frac{pd}{2t} \quad (1)$$

Longitudinal stress: σ_x

$$\sigma_x = \frac{pd}{4t} \quad (2)$$

p = external sea pressure

d = hull diameter

t = hull thickness

The hull thickness required for a collapse depth of 1500 feet was determined using Equation (1) with:

p = 666 psi

d = 33 feet

σ = 130,000 psi

The calculated hull thickness was 1.014 inches. Considering the corrosion allowance requirement and the availability of standard plate sizes, the hull thickness chosen for the Hy-130 submarine was 1.25 inches.

C. Stiffened Shell Calculations

In determining the strength of the pressure hull, it was necessary to consider the various means of failure that could occur. The pressure hull is a reinforced cylinder with internal or external frames. The failure mechanisms considered were shell yielding, shell buckling, and general instability. Shell yielding can be identified by the folding of the shell plate, resembling the creases in an accordion. Shell buckling occurs between, and often on both sides of, the frame. Both of the above failures are due to the plate being held in place by the frames and excessively loaded. Buckling can also cause the frames to trip over. The third type of failure, general yielding, occurs when the frames and shell fail as an entire unit. In the design of the pressure hull, sufficiently large factors of safety are used to insure the three types of failure do not occur. The factors of safety used in this submarine design were given in Table VI.

The sizing of the circular frames is an iterative process, where the scantlings are chosen and calculations performed to insure the frames are adequate. With Hy-80 submarines, the spacing between frames is approximately 10% of the hull diameter, i.e., 3.3 feet. With higher strength steels, such as Hy-130, the frames must be spaced closer in order to take full advantage of the higher strength steel. The frame calculations were based on the frame shown in Figure 12. Table VII lists the parameters used in the stiffened shell calculations.

1. Shell Instability and Frame Spacing

The pressure required for buckling is dependent on several factors, including the number of lobes formed. Fortunately, a formula given by

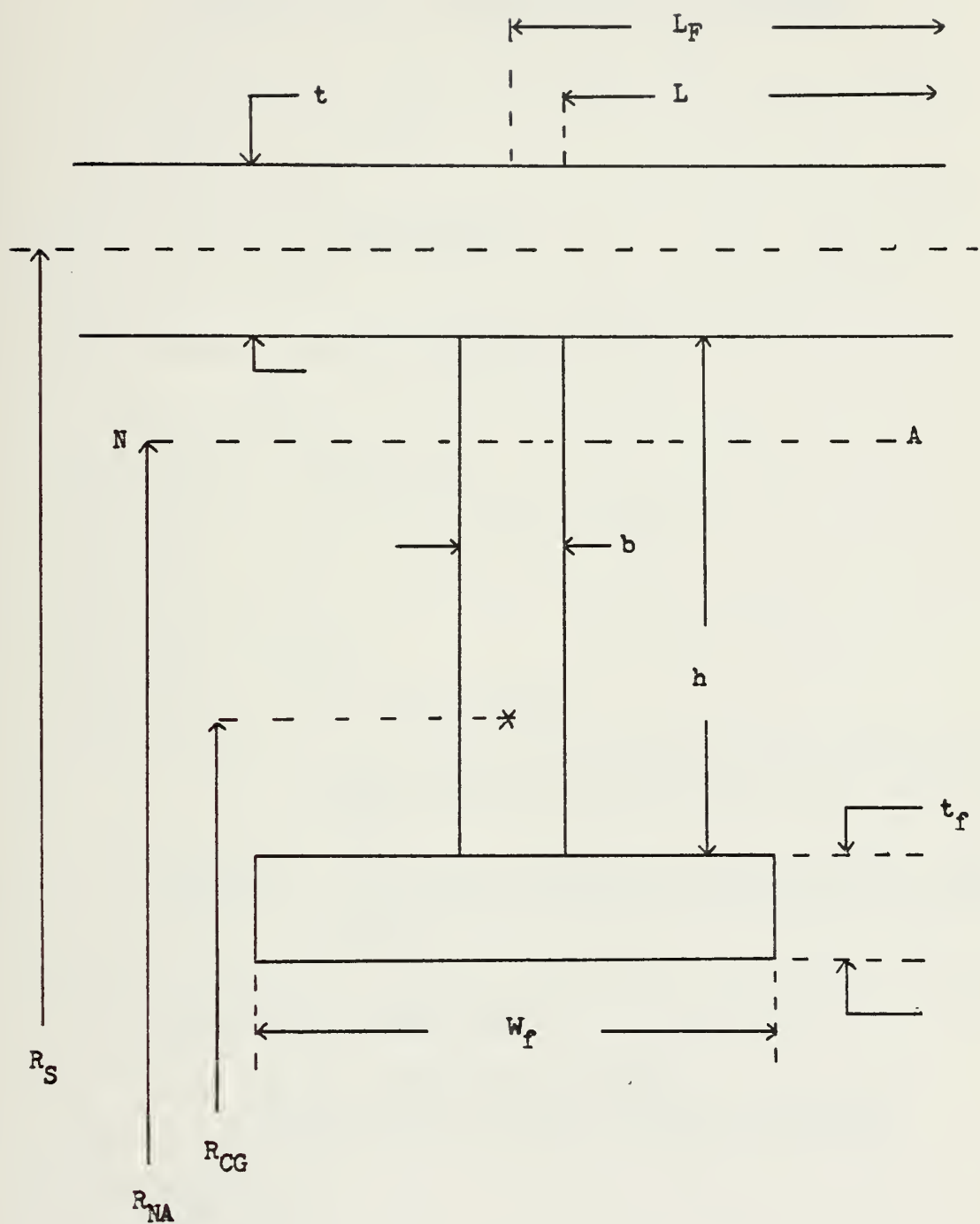


Figure 12- PRESSURE HULL SHELL AND FRAME ARRANGEMENT

Table VIIParameters Used in Stiffened Shell Calculations

t = thickness of pressure hull = 1.25 inches

h = length of frame web

b = web thickness

t_f = thickness of frame flange

w_f = flange width

R_S = radius to center of gravity of shell

D = hull diameter

R_{NA} = radius to neutral axis

R_{CG} = radius to center of gravity of frame

A_W = area of web

A_f = area of flange

$A_T = A_W + A_f$ = total area of frame

$B = bt/A_T + bt$ = ratio of shell area under the frame faying flange, to total frame area plus shell area under frame faying flange

$\theta = \frac{18.2 L/D}{\sqrt{100 t/D}}$ = a slenderness parameter dependent on shell thickness, frame spacing, and radius of curvature of shell plating

N, H, K = transcendental functions that define bending effect on shell due to local framing, where:

N = effect on deflection of frame

H = bending effect in shell reflected at midspan

K = bending effect in shell reflected near frame

$$N = \frac{\cosh\theta - \cos\theta}{\sinh\theta + \sin\theta}$$

$$K = \frac{\sinh\theta - \sin\theta}{\sinh\theta + \sin\theta}$$

$$H = - \frac{3 \sinh \theta/2 \cos \theta/2 + \cosh \theta/2 \sin \theta/2}{\sinh\theta + \sin\theta}$$

Table VII (cont'd.)

$$\beta = \frac{1.555[R_s t^3]^{1/2}}{A_T + bt} = \text{degree of flexibility provided by frame}$$

E = modulus of elasticity = 30×10^6 psi

v = Poisson's ratio = .3

P_{cr} = critical pressure required for failure or instability

L = unsupported frame spacing

L_F = frame spacing including web thickness = L+b

n = number of circumferential lobes in which the hull fails

m = $\frac{\pi R}{L_B}$ = number of longitudinal lobes in which the hull fails

L_B = length between King Frames or major bulkheads

I = moment of inertia

D_F = diameter to the center of gravity of frame

F = $b \left[\frac{1 + \frac{.85\beta}{B}}{1+\beta} \right]$ = relationship accounting for the length of shell included in the calculations

C = distance from the neutral axis of the frame to the steel fibers furthest away, usually the bottom of the flange

e = the amount of deviation of the shell and frame combination from a true circle, usually taken as equal to 1/2 t.

Windenburg [33], independent of the number of lobes has been developed.

The formula is given as:

$$P_{cr} = \left[\frac{2.42E}{(1-\nu^2)^{3/4}} \right] \left[\frac{(t/D)^{5/2}}{\frac{L}{D} - .45 \left(\frac{t}{D} \right)^{1/2}} \right] \quad (3)$$

For steel, with $\nu = .3$, the formula reduces to:

$$P_{cr} = \frac{2/6E (t/D)^{5/2}}{\frac{L}{D} - .45 (t/D)^{1/2}} \quad (4)$$

Since a degree of uncertainty exists, a factor of safety of 1.5 is applied to the collapse depth, i.e., 2.25 times the operating depth.

For this design, the critical pressure required for instability is 1000 psi. For Hy-80, t/D is approximately equal to .004, which results in the following:

$$P_{cr} = \frac{(2.6)(30 \times 10^6)(.004)^{5/2}}{L/D - .45(.004)^{1/2}} = 1000 \text{ psi}$$

$$\frac{L}{D} = \frac{(2.6)(30 \times 10^6)(.004)^{5/2}}{1000} + .45(.004)^{1/2}$$

$$\frac{L}{D} = .107$$

Therefore, for a Hy-80 design, the frame spacing is approximately 10% of the hull diameter as stated earlier.

The calculations for Hy-130 steel were made as follows:

$$t/D = \frac{1.125}{(33)(12)} = .00284$$

$$\frac{L}{D} = \frac{(2.6)(30 \times 10^6)(.00284)^{5/2}}{1000} + .45(.00284)^{1/2}$$

$$\frac{L}{D} = .0575$$

$$L = 22.77 \text{ inches}$$

Therefore, the unsupported frame spacing, L, for this design was calculated to be 22.77 inches, as compared to 39.6 inches for Hy-80.

2. Frame Scatlings

As the result of several iterations, the following frame scantlings were selected for the Hy-130 design. Forthcoming calculations will substantiate the adequate strength and stability of the frames.

$$L = 22.7 \text{ inches}$$

$$t = 1.125 \text{ inches}$$

$$b = .75 \text{ inches}$$

$$h = 12 \text{ inches}$$

$$w_f = 9 \text{ inches}$$

$$t_f = 1 \text{ inch}$$

Based on the above scantlings, the design parameters of Table VII were calculated to be:

$$L/D = .0575$$

$$t/D = .00284$$

$$t/2 = .5625 \text{ inches}$$

$$A_w = 9 \text{ in}^2$$

$$A_f = 9 \text{ in}^2$$

$$A_T = 18 \text{ in}^2$$

$$L_F = 23.45 \text{ inches}$$

$$bt = .84375 \text{ in}^2$$

$$A_T + bt = 18.84375$$

$$B = .044776$$

$$\theta = 1.9637 \text{ radians}$$

$$N = .9095$$

$$K = .5818$$

$$H = -.7193$$

$$\beta = 1.26$$

3. Shell Yielding

The highest stresses, and therefore the only ones needed to be calculated, are located at the inner side of the shell where it bends over the frame, and at the outside of the shell at the midbay. The respective formulas for calculating these stress levels were developed by von Sanden and Guenther [31]. The equations are commonly known as 92 and 92A.

92: axial stress

$$P_{cr} = \frac{2 \sigma_y t/D}{.5 + 1.815 \left(\frac{.85 - B}{1 + \beta} \right) K} \quad (5)$$

92A: circumferential stress

$$P_{cr} = \frac{2 \sigma_y t/D}{1 + H \left(\frac{.85 - B}{1 + \beta} \right)} \quad (6)$$

Calculations using Equations (5) and (6) resulted in critical pressures of 842.69 psi and 992.8 psi respectively. Therefore, the submarine would have to exceed designed depths to experience shell yielding, indicating the adequacy of the structure.

4. Frame Instability

The critical pressure for frame instability is given by von Sanden and Guenther, and is commonly known as formula 88.

$$P_{cr} = \frac{24EI}{D_F^3 L_F} \quad (7)$$

The moment of inertia calculations were calculated as follows:

<u>Item</u>	<u>area</u>	<u>arm</u>	<u>moment</u>	<u>d</u>	<u>Ad²</u>	<u>I_o</u>
Shell	26.6625	0	0	3.954	416.844	2.782
Web	9	6.5625	59.0625	2.6085	61.238	108
Flange	<u>9</u>	13.0625	<u>117.5625</u>	9.1085	<u>746.682</u>	<u>.75</u>
	44.6625		176.625		1224.764	111.532

The assumed neutral axis, N.A., was taken as the center of the shell.

$$y = \frac{\sum \text{moments}}{\sum \text{area}} = 3.954$$

Therefore, the actual N.A. was calculated to be 3.954 inches below the assumed N.A.

$$d = \text{arm} - \bar{y}$$

I_o = moment of inertia about own axis

$$I = Ad^2 + I_o = 1336.296 \text{ in}^4$$

$$y \text{ to center of gravity of frame} = \frac{\sum \text{moments}}{A_f + A_w} = 9.8125 \text{ in}$$

$$D_F = D_s - 2y = 376.3725 \text{ in}$$

Using Equation (7), the critical pressure for frame instability was calculated to be 769.55 psi. Again, adequate stability is provided since the designed collapse pressure is 666 psi.

5. General Instability

With general instability, the structure will fail in large lobes between two strong points such as major bulkheads or king frames. The pressure required for this failure was calculated from a formula developed by Kendrick and simplified by Brant [32]. Since the factor of safety is 3.75, the 5% error due to the simplification is not excessive.

$$P_{cr} = \frac{Et}{R_s} \frac{m^4}{(n^2-1 + \frac{m^2}{2})(n^2+m^2)} + \frac{(n^2-1)EI}{R_s^3 L} \quad (8)$$

The parameter m , number of longitudinal lobes, is dependent upon the king frame or major bulkhead spacing, L_B . Normally, L_B is taken as one to two hull diameters. This author chose 1.5D, or 49.5 feet, as a value for L_B . The nearest whole integer value for m is then equal to one. Calculations were then performed by assuming $n=2, 3, 4$, etc. Using Equation (8), the minimum critical pressure for general instability was calculated to be 2020.62 psi for n equal to three. Adequate stability is assured since the designed pressure is 1665 psi.

6. Frame Stress Analysis

The total stress, σ_T , in the frame is comprised of bending stress (σ_B) and stresses due to compression (σ_c). The total stress must be less than the yield stress of the structural steel. The compressive stress was calculated using a formula developed by von Sanden and Guenther, and presented in Reference [27].

$$\sigma_c = \frac{R_{cG} F P}{A + b t} \quad (9)$$

The bending stress component was calculated using a formula developed by Kendrick, and also presented in Reference [27]

$$\sigma_B = \frac{E c e (n^2 - 1) P}{(R_{NA})^2 (P_{cr} - P)} \quad (10)$$

The compressive stresses were computed to be 55,002 psi. Bending stresses amounted to 18,818 psi. Therefore, the total stress was calculated as 73,820 psi, which is less than the yield stress of Hy-130.

7. Summary of Frame Scantlings and Weight

Table VIII summarizes the scantlings selected for the frames, and the weight of the frame components. The weight given for the shell is based on the frame spacing, L_F , and the pressure hull thickness, t . Compared to results presented in reference [30] for Hy-80 designs, the total weight of the Hy-130 frame and shell section represents a 20-25% decrease in weight. This compares favorably with weight curves presented in reference [27].

D. King Frames

The formulas used in this analysis were developed on the basis that these would be internal bulkheads supporting the pressure hull at regular intervals. In older designs, these bulkheads and their spacing were based on the premise that the main ballast tanks would support the submarine if one of the internal compartments flooded. For practical considerations, the bulkhead spacing was 1.5 to 2 hull diameters. However, with the coming of nuclear power, which necessitated larger compartments

Table VIIISummary of Frame Scantlings and Weight

<u>Component</u>	<u>t(in)</u>	<u>h(in)</u>	<u>w(in)</u>	<u>Weight (tons)</u>
pressure hull	1.25	-	23.45	4.595
frame web	.75	12	-	1.363
frame flange	1.0	-	9	1.317
frame and shell	-	-	-	7.275

1 long ton = 2240 lbs

Density of steel = .2833 (lbs/in³)

flooded. For practical considerations, the bulkhead spacing was 1.5 to 2 hull diameters. However, with the coming of nuclear power, which necessitated larger compartments and a reduction in reserve buoyancy (smaller ballast tanks), it was no longer possible to design with the above philosophy. The structural bulkhead was eliminated and replaced with a large reinforcing ring which is frequently referred to as a king frame or deep frame. They are placed in the compartment at regular intervals equal to one to two hull diameters. In this analysis, a maximum major bulkhead or king frame spacing of 1.5 diameters was used.

1. Selection of Scantlings

To calculate the size of the king frame, an analysis is performed as was done for the normal frames. Since the king frame is large, N is equal to 1.0. Shell yielding and buckling pressures do not need to be recalculated as they are a function of the normal frames. However, the normal frames placed next to king frames should have their spacing, L_F , reduced to approximately 80% of the normal L_F . The amount of shell (pressure hull) effectively contributing to the king frame was assumed to be 30t. The n and P_{cr} values used in king frame stability analysis are the same as those calculated for the normal frames.

Since the same calculations were carried out as for the normal frames, the calculations were not repeated here. Iteration resulted in selection of the following scantlings for the king frames:

Web thickness (b) = 1.5 inches

Web height (h) = 34 inches

Flange width (W_f) = 24 inches

Flange thickness (t_f) = 1.5 inches

Weight of web = 7.281 tons

Weight of flange = 4.632 tons

E. Hemispherical End Closures

The end closures for this design are hemispherical with a radius of 16.5 feet. Stability of thin-walled spheres is given by Equation (11). The equation is adequate for spheres with R/T values of 20 through 500 [27].

$$P_{cr} = 1.2E (t/R)^{9/4} \quad (11)$$

For a critical pressure of 666 psi, the hemispherical shell thickness was computed to be 1.56 inches. Based on corrosion allowance requirements and standard plate sizes, a thickness of 1.75 inches was chosen. It should be noted that Equation (11) does not take into account the strength of different steels. Approximately 1/2 inch Hy-130 would be sufficient if strength were the only consideration. However, prevention of failure by buckling necessitates the heavier shell, and does not allow full advantage to be taken of the high strength of Hy-130. Therefore, it would probably be more economical to use HTS or mild steel for the end closures, assuming there would be no difficulties in joining the substitute steel to Hy-130. In any case, this study assumed that the welding parameters would be based on Hy-130 welding requirements to insure an adequate transition joint.

CHAPTER IV

ESTIMATION OF WELDING REQUIRED

A. Limitations on Welding Estimate

The number of joints, and amount of required welding computed for the Hy-130 submarine, were based on the structural design completed in the previous chapter. Chapter III, however, was not intended to be a detailed structural design and internal arrangement analysis, but was to provide a means for estimating a large amount of the welding required. The estimated amount of welding is therefore conservative. In reality, additional welding would be required for internal structural bulkheads and stiffeners, external wing bulkheads and stiffeners, equipment foundations, deck grillages, foreward and after bodies of revolution, etc. In terms of the weight of weld metal deposited by conventional welding techniques, this author estimates that this analysis represents approximately 50-60% of the required structural welding for the entire submarine. This estimate was arrived at by reviewing actual designs.

B. Construction Considerations

The construction of the circular pressure hull is accomplished by fabricating the stiffened cylinder in sections, and then welding the sections together. Based on a conversation with Captain Jackson, a retired Naval Officer and noted submarine designer, these individual sections are made approximately 3 frame spaces in length. With a Hy-80 submarine, each cylindrical section would be approximately 10 feet long. Due to the smaller frame spacing in the Hy-130 design, a stiffened cylinder 10 feet in length corresponds to 5 frame spaces. In this analysis, a

stiffened cylinder length of 10 feet was assumed for the purpose of determining the number of sections to be joined. In addition to circular welds, seam welds must also be made on the Hy-130 hull plate after being rolled to the required diameter.

C. Summary of Welding Required

Table IX summarizes the amount of welding required for the Hy-130 submarine shown in Figure 11, Chapter III. The length of circumferential welding of the pressure hull was based on the radius to the mid-thickness of the pressure hull plating, 197.375 inches. The radius of the frame web to pressure hull joint was taken as 196.75 inches, and flange to web radius as 184.75 inches. Seam welding of the pressure hull was based on the overall length of the circular pressure hull, 337 feet. The radius of the king frame web to pressure hull joint was taken as 196.75 inches, and flange to web radius as 162.75 inches.

Table IXSummary of Welding Required

Number of stiffened shell sections	34
Number of welds required to join shell sections	33
linear feet for 1 weld	103.3 ft.
total linear feet	3,409 ft.
Pressure hull seam welding	337 ft.
Number of internal normal frames	173
Web to pressure hull welding	17,819 ft.
Flange to web welding	16,727 ft.
Number of internal king frames	5
Web to pressure hull welding	515 ft.
Flange to web welding	426 ft.
Number of hemispherical end closures	2
Welding length	207 ft.
Total linear feet of welding required	39,440 ft.

CHAPTER V

LASER EXPERIMENTAL WELDING

A. Scope of Research

A series of five experiments was conducted to determine technical aspects of laser welding of thick plate, restrained butt joints. Three specimens were used to measure laser penetration capabilities. The two remaining specimens were instrumented, and used to measure temperature changes and thermal strains which occurred during laser welding. The temperature and strain data was recorded and plotted for future use with computer programs currently under development.

All experiments were conducted with HY-130 steel, a quenched and tempered steel under development by the U.S. Navy for future use in submarines. Laser power, as measured at the plate surface, was maintained at 12 KW.

B. Technical Aspects of Strain Measurements

Strain measurements were made on the surface of the metal plate by use of adhesive bonded, electric resistance strain gages. This method of strain measurement is a convenient and accurate method of measurement. The total resistance change in the strain gage, ΔR , consists of resistance changes due to mechanical strains and thermal strains in the specimen, as well as thermal strain and thermo-electric changes in the strain gage itself. The total resistance change can therefore be expressed as follows:

$$\Delta R = \Delta R(e) + \Delta R(p) + \Delta R(t) + \Delta R(g) \quad (12)$$

where

$\Delta R(e)$ = resistance change due to elastic strain in the specimen

$\Delta R(p)$ = resistance change due to plastic strain in the specimen

$\Delta R(t)$ = resistance change due to temperature induced thermal strain in the gage

$\Delta R(g)$ = resistance change due to thermal electric effects in the gage

In studying the thermal strains due to welding, only $\Delta R(e)$ and $\Delta R(p)$ are of interest. Therefore, $\Delta R(t)$ and $\Delta R(g)$ must be separated out of the data obtained. Fortunately, the gage manufacture provided the necessary corrections throughout the temperature range considered. The corrections provided were in the form of a curve of apparent strain (A.S.) versus temperature. Therefore, Equation (12) becomes:

$$E\Delta R(e) + E\Delta R(p) = E\Delta R - A.S. \quad (13)$$

or,

$$\epsilon_T = \epsilon_m - A.S. \quad (14)$$

where

ϵ_T = total actual strain due to welding

ϵ_m = measured strain

A.S. = strain gage correction

C. Apparatus

1. Specimen Preparation

All five specimens were made from one inch thick HY-130 plate. Specimen V measured 8" x 14 3/4", and was used for bead on plate welding and setting of welding parameters. Specimens I through IV consisted of two plates each, with each plate measured 5.5" x 14 3/4". Therefore, after welding, specimens I-IV measured 11" x 14 3/4". The weld joint configuration chosen for specimens I-IV was a flat butt joint. The plates were cut using a Kalamazoo horizontal band saw, with no additional edge preparation. The surfaces of the plate near the weld line were mechanically cleaned to remove potential weld contaminates. Specimen dimensions and weld direction are shown in Figure 13.

2. Instrumentation

Strain on the surface of specimens II and IV was measured using electric resistance strain gages. The gages were placed at varying transverse distances from the weld line, but at the same longitudinal position. A 90° pair of strain gages was installed at each transverse

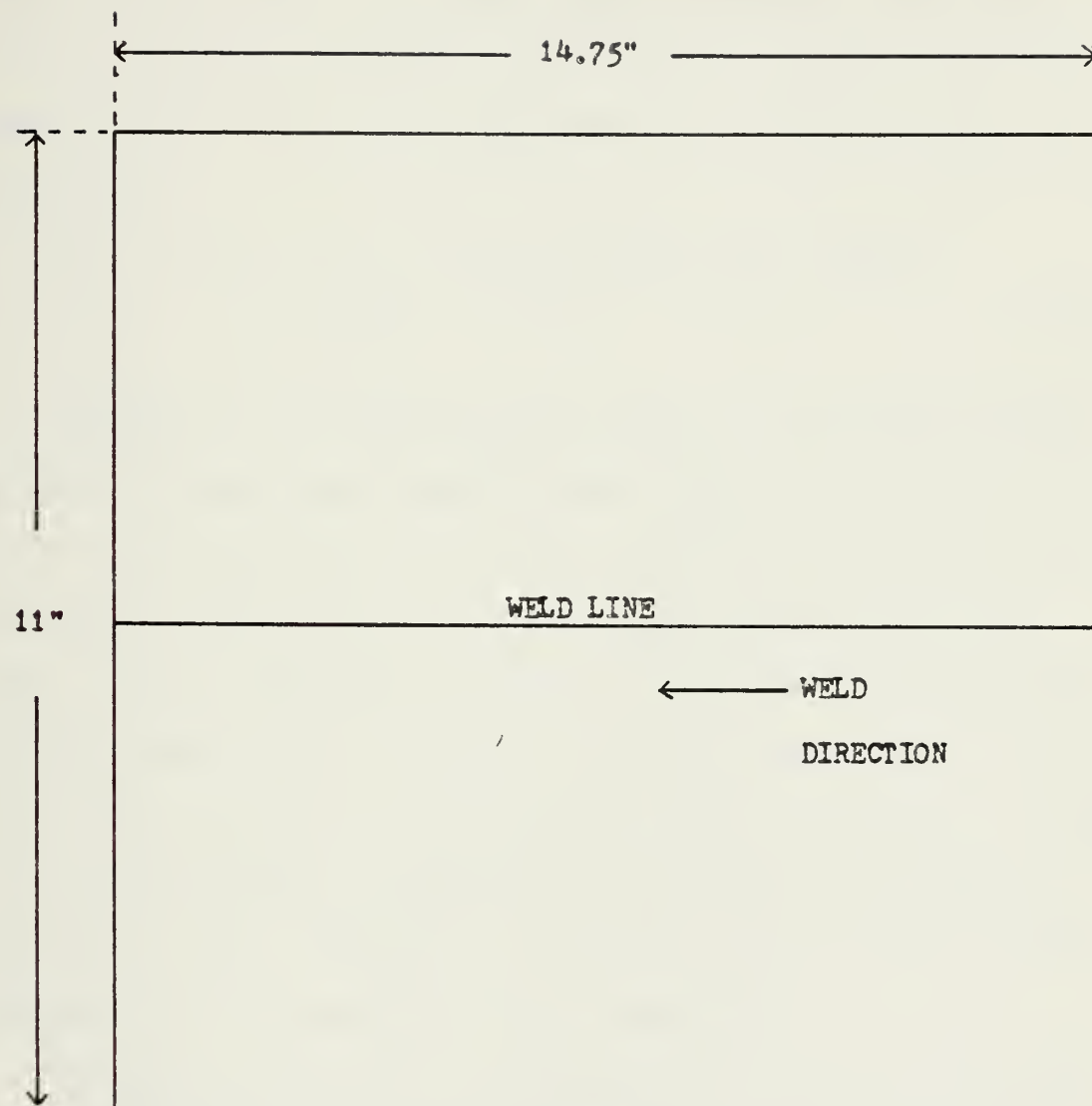


Figure 13- LASER WELDING SPECIMENS I, II, III, and IV

position to allow the simultaneous measurement of both longitudinal and transverse strain. The strain gage specifications are shown in Table X. The curve of apparent strain versus temperature for these gages is shown in Figure 14. The apparent strain equation for this curve is:

$$\begin{aligned} \text{A.S.} = & -91.37 + 2.71T - 2.33 \times 10^{-2}T^2 + 5.31 \times 10^{-5}T^3 \\ & - 2.40 \times 10^{-8}T^4 \end{aligned} \quad (15)$$

Temperature was measured on the surface of the welding specimens by use of chromal/alumel adhesive bonded thermocouples referenced to 32°F. The thermocouples were placed at transverse positions from the weld line corresponding to the transverse positions of the strain gages. In the longitudinal direction, the thermocouples were placed only 3/8" ahead of the center line of the strain gage pair. At the welding speeds used, the time difference between the laser spot passing the strain gages and then reaching the thermocouples was limited to less than a second. Therefore, the measured values of strain closely corresponded to the measured values of temperature.

Temperature and strain were simultaneously read out on a twelve channel, continuous recording viscorder. Thermocouple and strain gage locations are shown in Figure 15.

D. Experimental Procedure

All welding was performed using a continuous-wave electric industrial CO₂ laser. The multikilowatt capable laser and F-21 optics were made available for experimental welding by AVCO EVERETT METAL WORKING LASERS of Somerville, Massachusetts. In all cases, Helium

Table XStrain Gage Properties

Gage Designation	FAET-12D-12-56
Manufacturer	BLH Electronics
Grid Dimensions	.127 inches
Temperature Range	-100 to 500°F
Resistance	120 ohms
Gage Factor	2.01
Cement	EPY-500

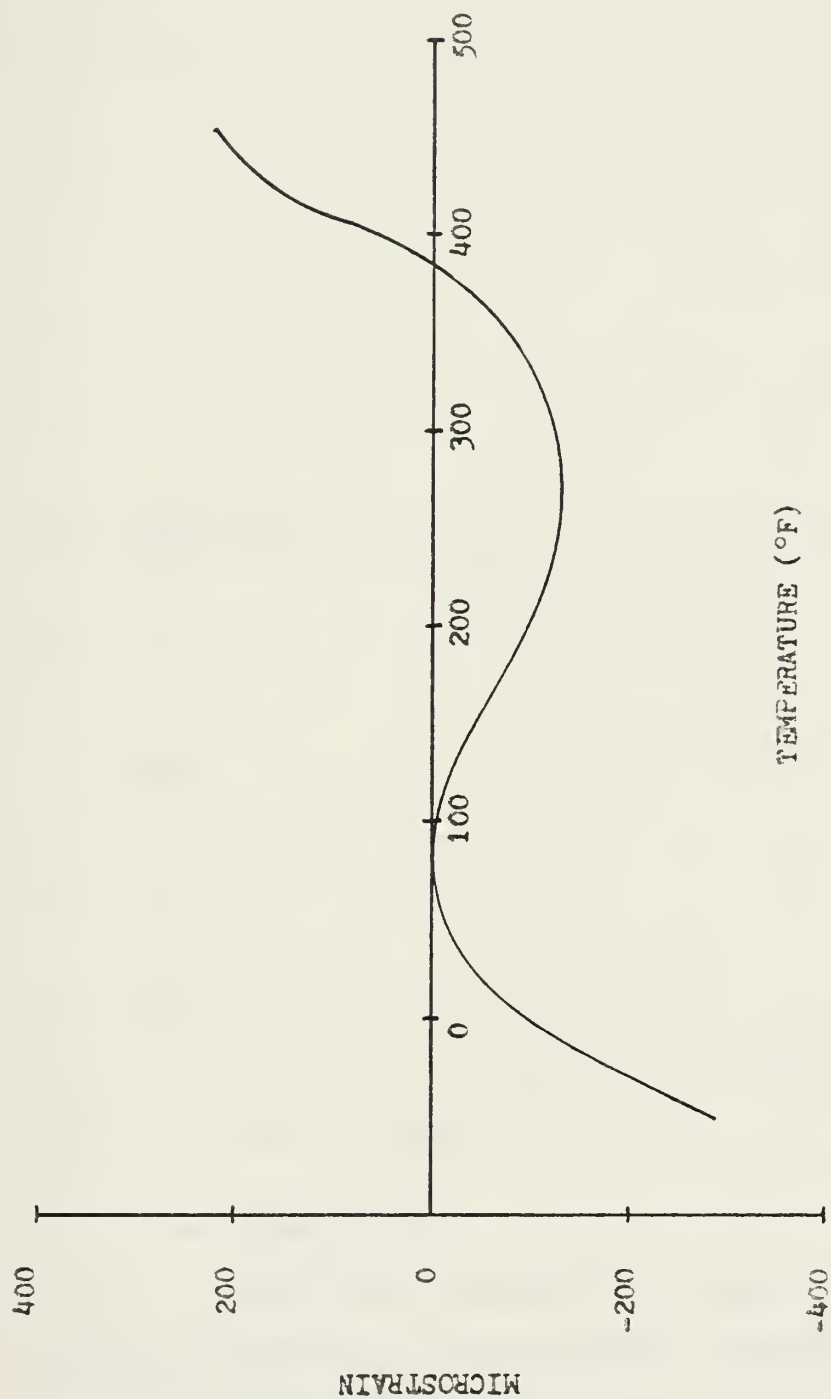
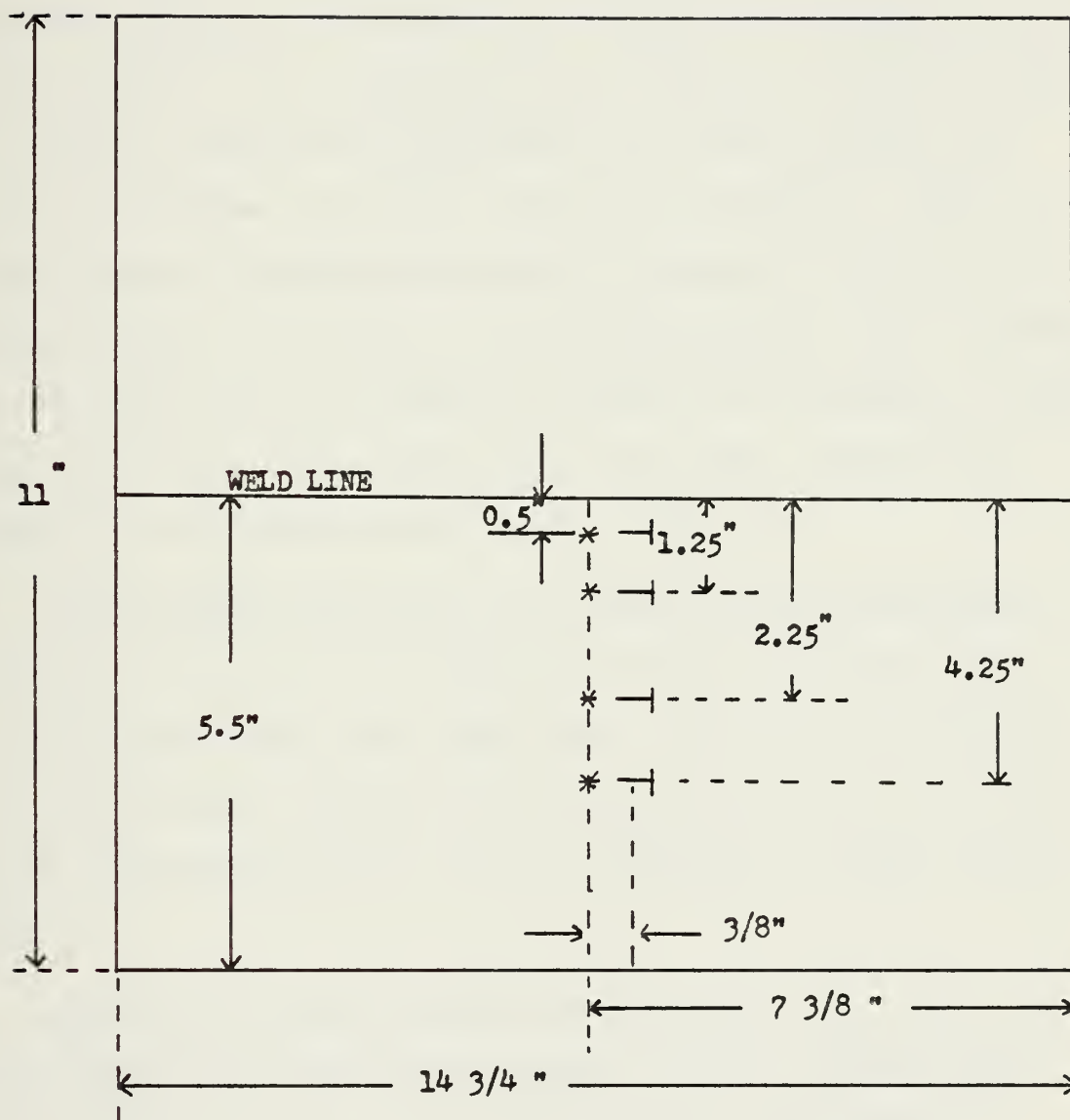


Figure 14- EFFECT of TEMPERATURE on APPARENT STRAIN FOR STRAIN GAGE PAIR



* THERMOCOUPLES

—| LONGITUDINAL AND TRANSVERSE STRAIN GAGE PAIR

Figure 15- THERMOCOUPLE AND STRAIN GAGE LOCATIONS ON HY-130
SPECIMENS II AND IV

shielding gas was provided by an off axis nozzle. Gas flow rate was 200 CFH at 30 psi. Pre-heat was not provided prior to welding.

Initial estimates of laser penetration were made using specimen V. Six bead-on-plate passes were made at varying welding speeds and beam focal lengths. At the completion of the 6 passes, the plate was cut and etched to determine the penetration associated with each pass. Table XI summarizes the results obtained with specimen V. Based on these results, the welding parameters used during the third bead-on-plate pass were also used for the remaining specimens, I-IV. Therefore, the welding speed for all remaining specimens was 30 inches per minute. Power, as measured on the work surface, was 12 KW. Electric power supplied to the laser was approximately 140 KW.

Actual welding penetration was determined using uninstrumented specimens I and III. Each specimen was clamped in position on the work table and welded with a single pass. Joint gap was essentially zero at the start of welding. As expected with 12 KW of laser beam power, full penetration of 1" was not achieved with a single welding pass.

Based on the results obtained with specimens I, III, and V, two pass welding was utilized with specimens II and IV. The specimens were clamped to the work table prior to welding. The mechanical restraint imposed by the clamping resulted in measurable longitudinal and transverse strains at the strain gage locations. After recording these strains, the 8 visicorder strain channels were reset to zero in preparation for measuring thermal strains due to welding.

Table XISpecimen V - Bead-on-Plate Welding

<u>Pass</u>	<u>Focal length (inches)</u>	<u>On Work KW</u>	<u>Welding Speed (IPM)</u>	<u>Penetration (inches)</u>
1	33 1/4	12	40	20/32
2	33 1/4	12	35	20/32
3	33 1/4	12	30	22/32
4	33	12	40	19/32
5	33	12	35	20/32
6	33	12	30	21/32

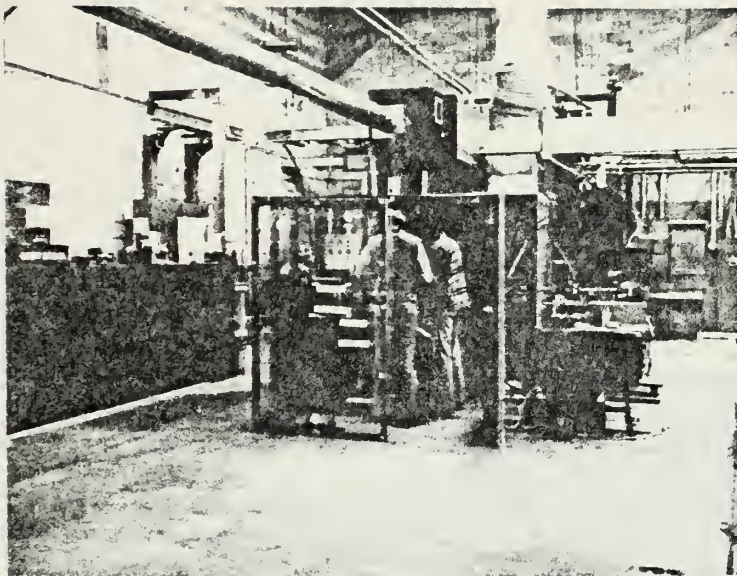
Metal shims were placed under the extreme ends of specimens II and IV prior to clamping to the work table. The shims provided for an air gap between the HY-130 plate and the metal work table over most of the weld length. This minimized the heat transfer to the work table. Tack welds at each end, and both sides, were made on specimen IV prior to welding. Specimen II was welded without prior tack welding.

Welding pass #1 was made on the surface containing the thermocouples and strain gages. The visicorder was actuated the moment the laser spot commenced welding. At the end of the weld line, laser power was terminated. The visicorder continued to record temperatures and strains continuously for 3 minutes, and then intermittently every minute until the specimens approached room temperature. When specimens cooled sufficiently, the clamping was released. Longitudinal and transverse strain changes due to releasing the mechanical restraint were recorded.

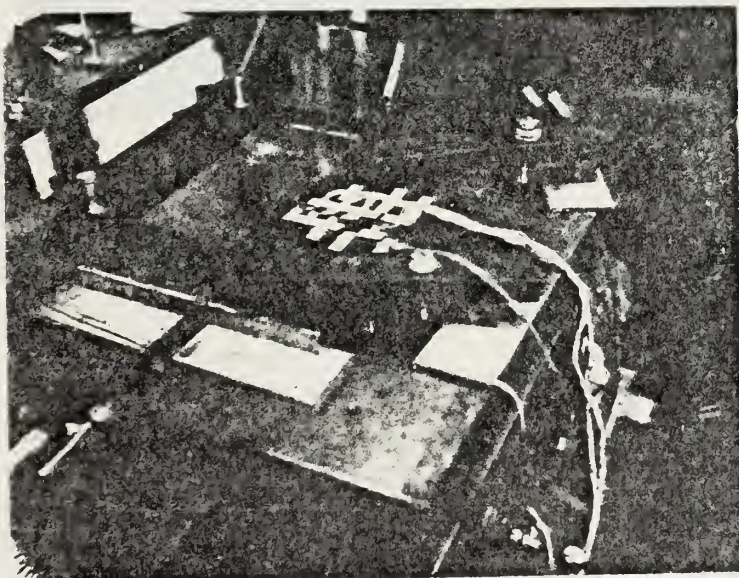
Welding pass #2 was made by turning the welded plates and instrumentation over, and then reclamping. Strains due to clamping were recorded and visicorder reset to zero in preparation for welding pass #2. Temperature and strains due to welding were then recorded as done for the first pass. It should be emphasized that the specimens were instrumented on only one side. Therefore, the temperature and strains recorded for the second pass measured the effects of welding the opposite side of the plate. Since specimen II was not tack welded, the joint gap associated with the second pass was .020 inches.

Only very slight undercutting was experienced for the specimens not tack welded.

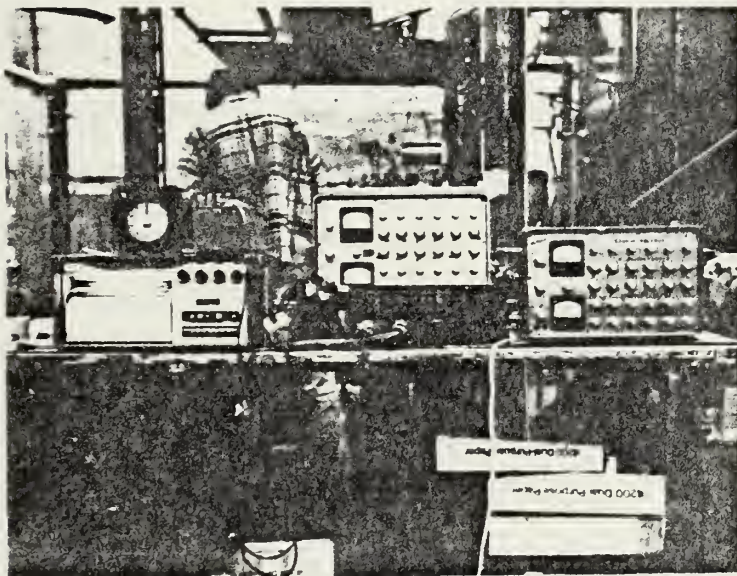
The accompanying photographs show various aspects of the experimental welding. Photograph #1 presents a view of the work area. The 15 KW capable laser is located directly behind the plexiglass enclosure. The ducting seen in the upper right hand portion of the picture allows passing the laser beam to additional work areas. The welding specimen, work table, and hold down clamps are shown in the second photograph. The off-axis helium gas nozzle located just above the specimen can also be seen. The visicorder and associated instruments for recording temperatures and strains are shown in photograph #3.



Photograph #1- LASER WORK AREA



Photograph #2- HY-130 WELDING SPECIMEN



Photograph #3- INSTRUMENTS USED IN THE RECORDING OF
TEMPERATURE AND STRAIN DATA

CHAPTER VI

EXPERIMENTAL RESULTS

A. Laser Penetration

Specimen I was cut to determine the single pass penetration obtained with 12 KW of laser beam power. The penetration was found to be 23/32 inches. Cutting of specimen IV revealed the same results. Therefore, the potential exists for welding 1.5 inch thick HY-130 plate with 12-13 KW of beam power, using two welding passes, one from each side of the plate.

B. Presentation of Temperature and Strain Data

The experimental results are presented as temperature versus time, longitudinal strain versus time, and transverse strain versus time. The time axis refers to the time elapsed from the commencement of welding until the specimen cooled. Temperature is measured in degrees Fahrenheit. Longitudinal and transverse strains are presented in units of microstrain, which equals 10^{-6} in/in.

Figures 16-35 present the experimental results for HY-130 specimen II. The strain measurements 4.25" from the weld line were minimal and therefore are not presented. The results obtained for specimen IV were nearly identical to those obtained with specimen II, and therefore are also not presented. The strain changes which resulted from clamping and unclamping specimen II are given in Table XII.

Table XIIMechanical Imposed Strains on Specimen IIPass # 1

<u>Location</u>	<u>Longitudinal change clamping</u>	<u>Longitudinal change unclamping</u>	<u>Transverse change clamping</u>	<u>Transverse change unclamping</u>
.50	-90	+200	+20	-20
1.25	-80	+180	+25	-10
2.25	-70	+120	+15	-20

Pass # 2

<u>Location</u>	<u>Longitudinal change clamping</u>	<u>Longitudinal change unclamping</u>	<u>Transverse change clamping</u>	<u>Transverse change unclamping</u>
.50	+40	+20	+50	-50
1.25	+25	0	+55	-30
2.25	+25	-20	+50	-30

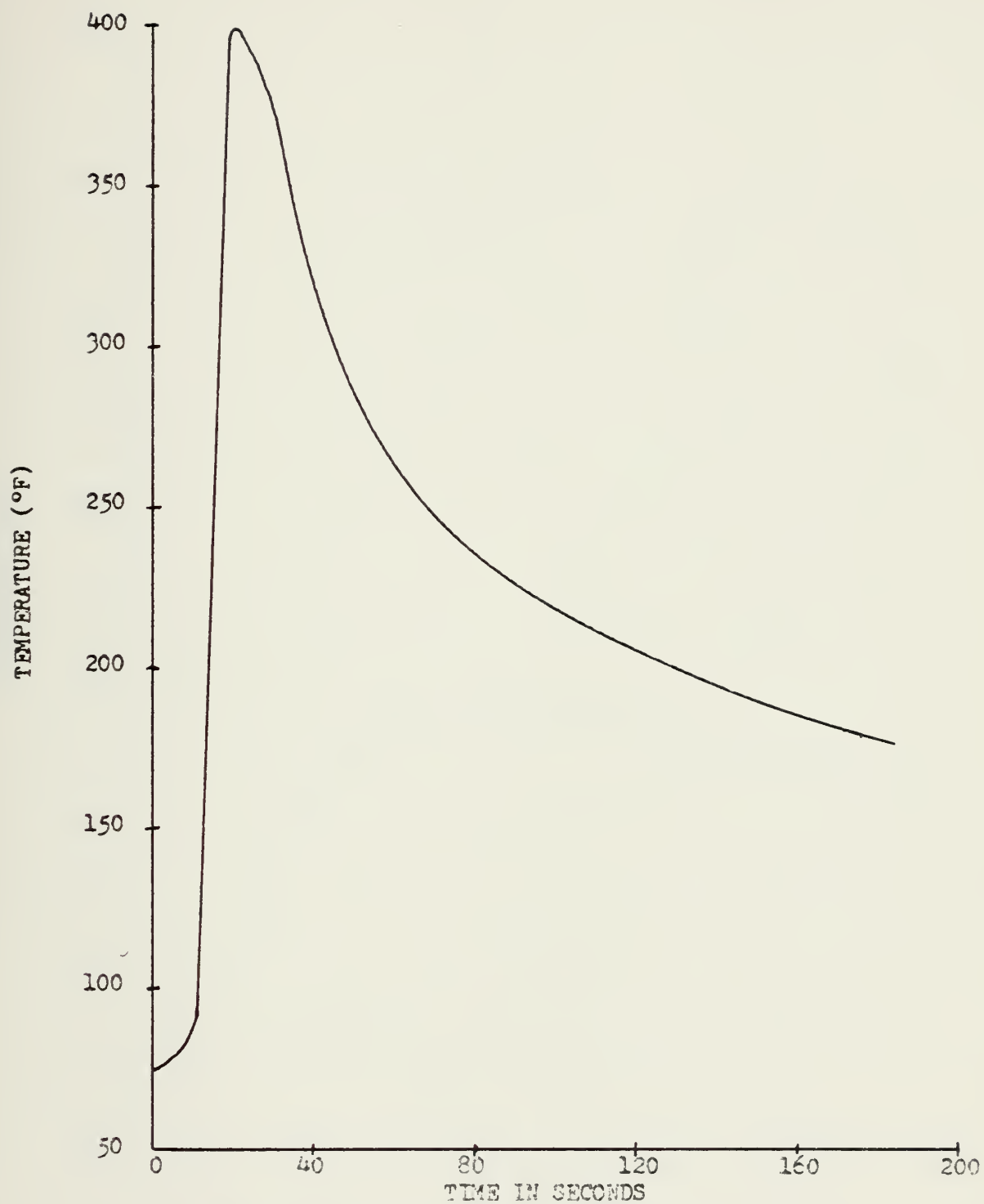


Figure 16-HY 130 SPECIMEN II, TEMPERATURE VERSUS TIME

.50" from WELD LINE, PASS #1

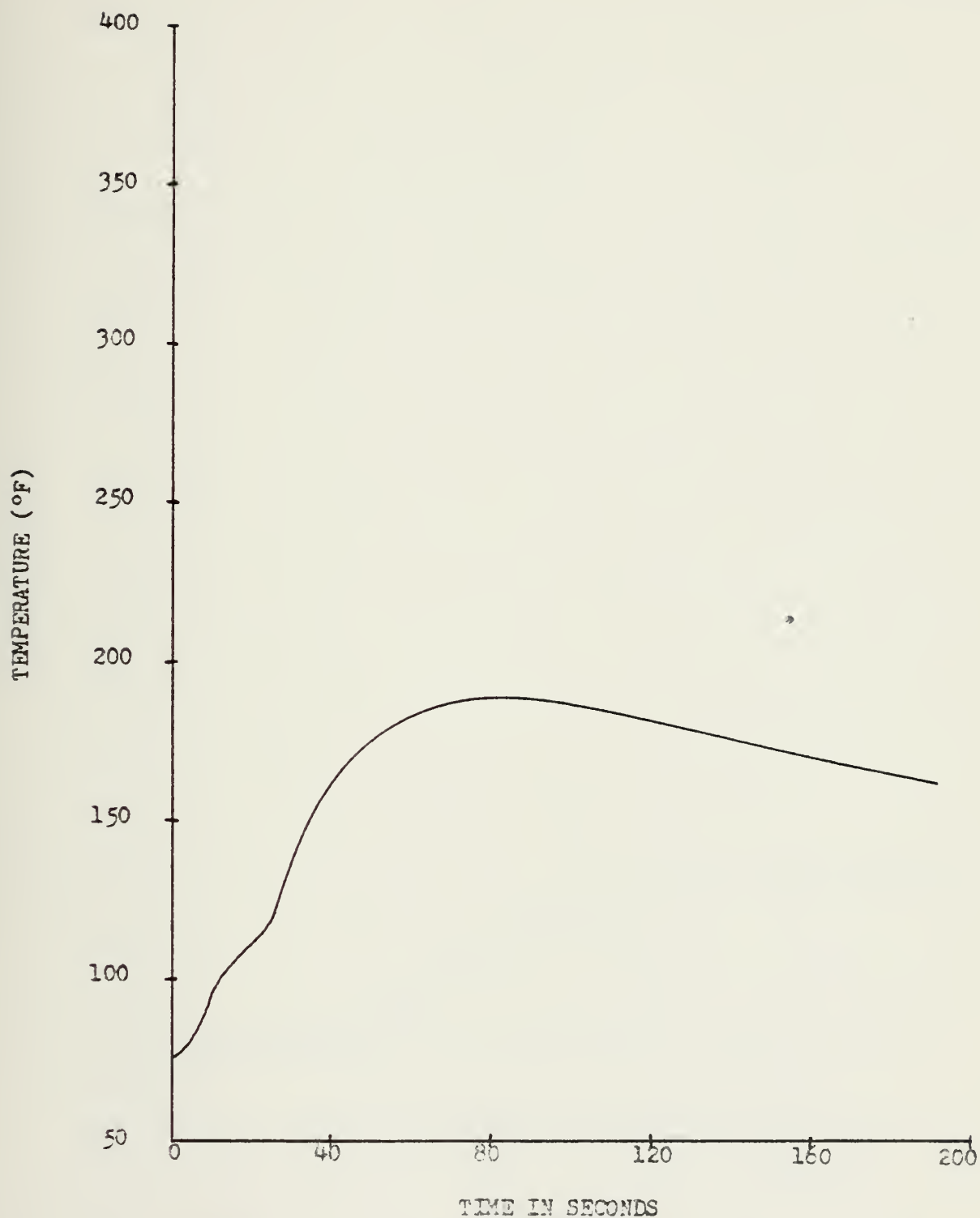


Figure 17- HY 130 SPECIMEN II, TEMPERATURE VERSUS TIME

1.25" from WELD LINE, PASS #1

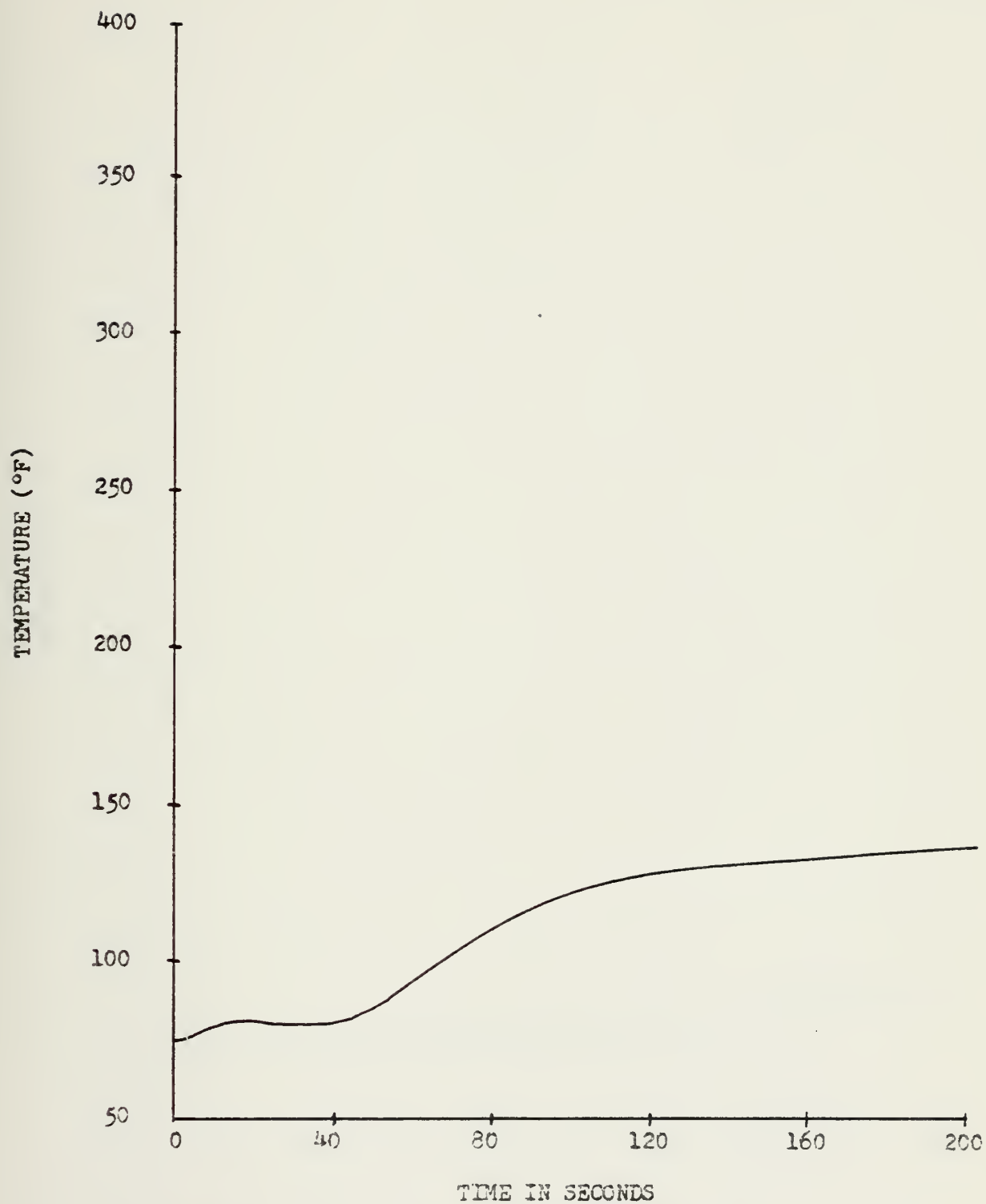


Figure 18- HY 130 SPECIMEN II, TEMPERATURE VERSUS TIME

2.25" from WELD LINE, PASS #1

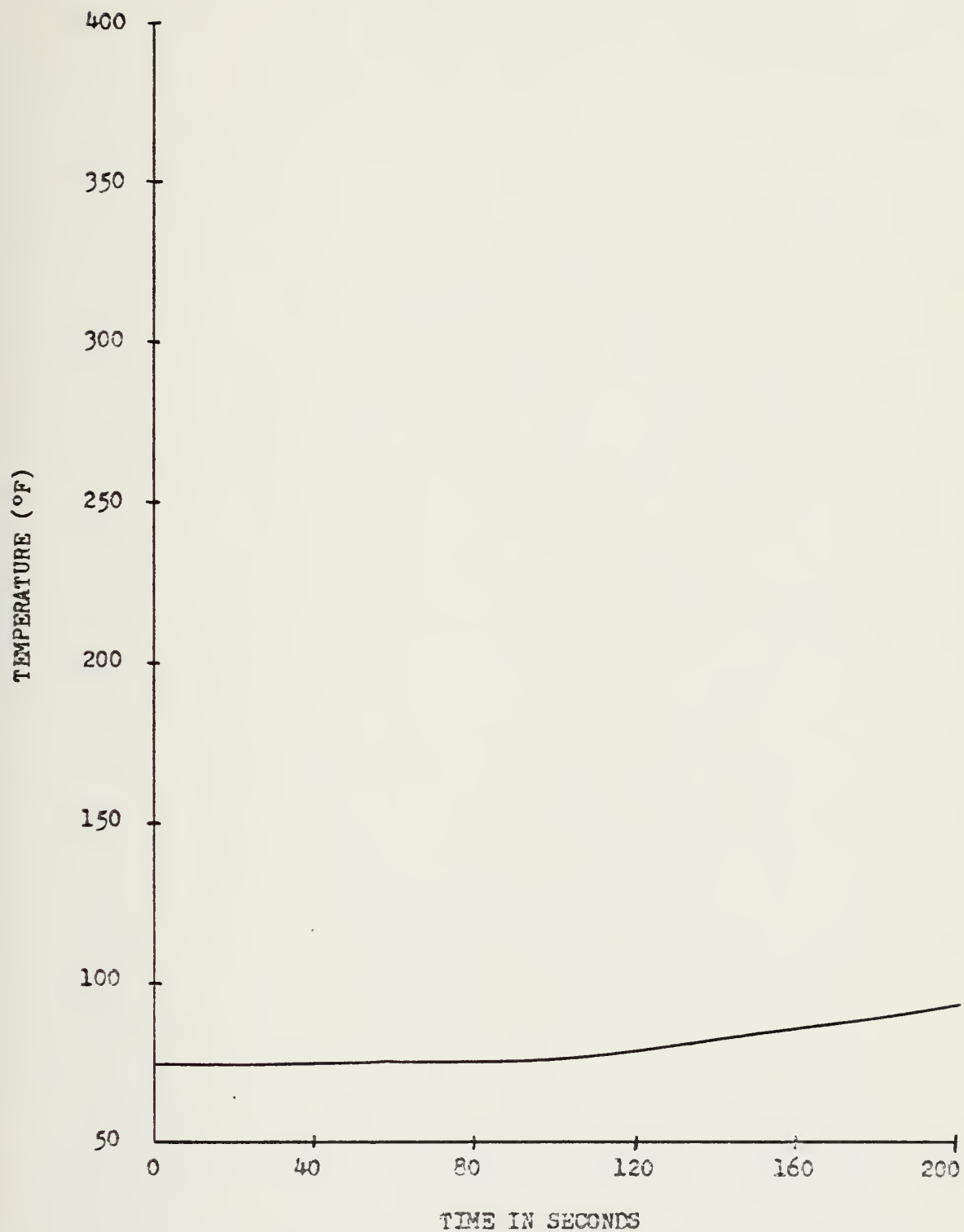


Figure 19- HY 130 SPECIMEN II, TEMPERATURE VERSUS TIME

4.25" from WELD LINE, PASS #1

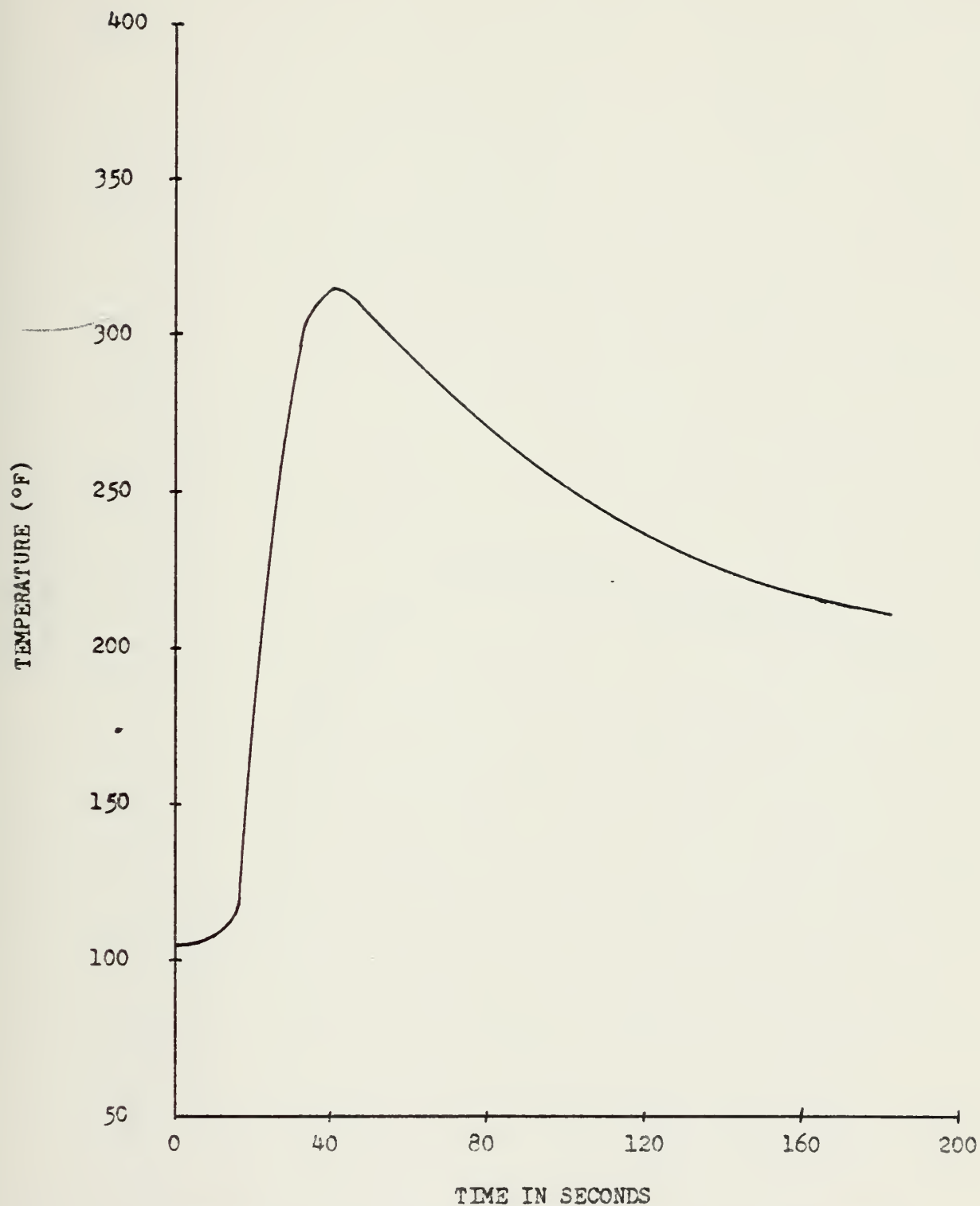


Figure 20- HY 130 SPECIMEN II, TEMPERATURE VERSUS TIME

.50" from WELD LINE, PASS #2

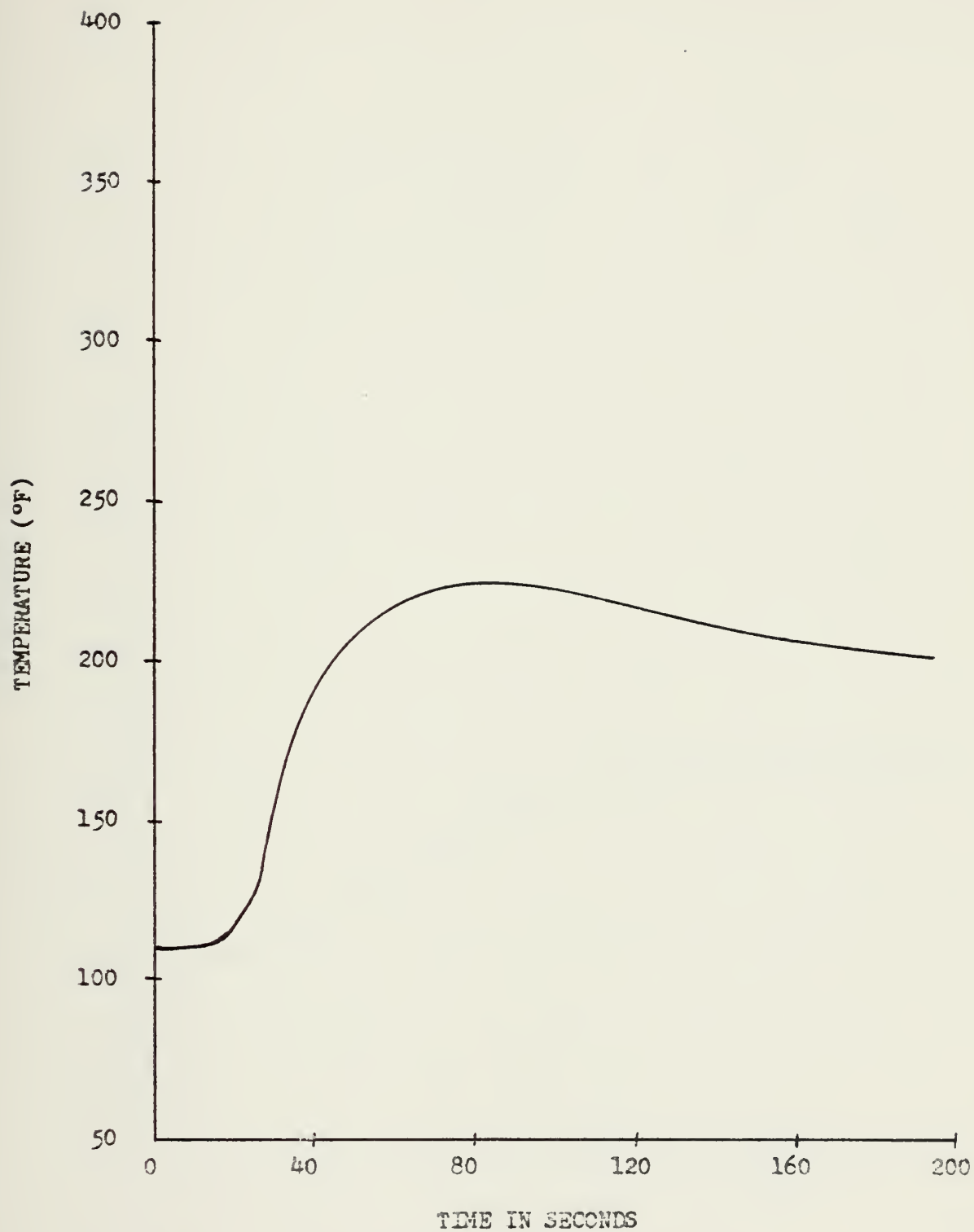


Figure 21- HY 130 SPECIMEN II, TEMPERATURE VERSUS TIME

1.25" from WELD LINE, PASS #2

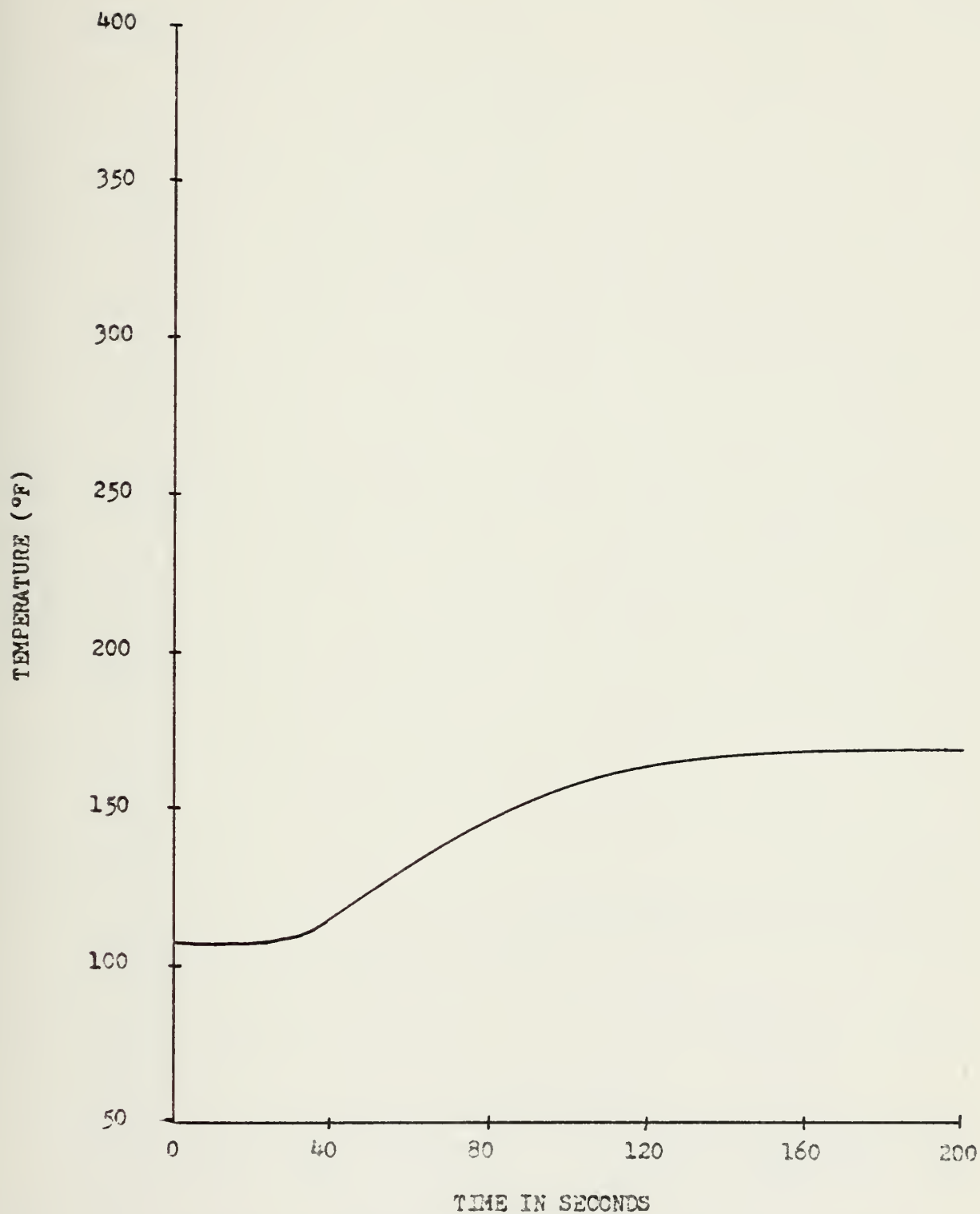


Figure 22- HY 130 SPECIMEN II, TEMPERATURE VERSUS TIME

2.25" from WELD LINE, PASS #2

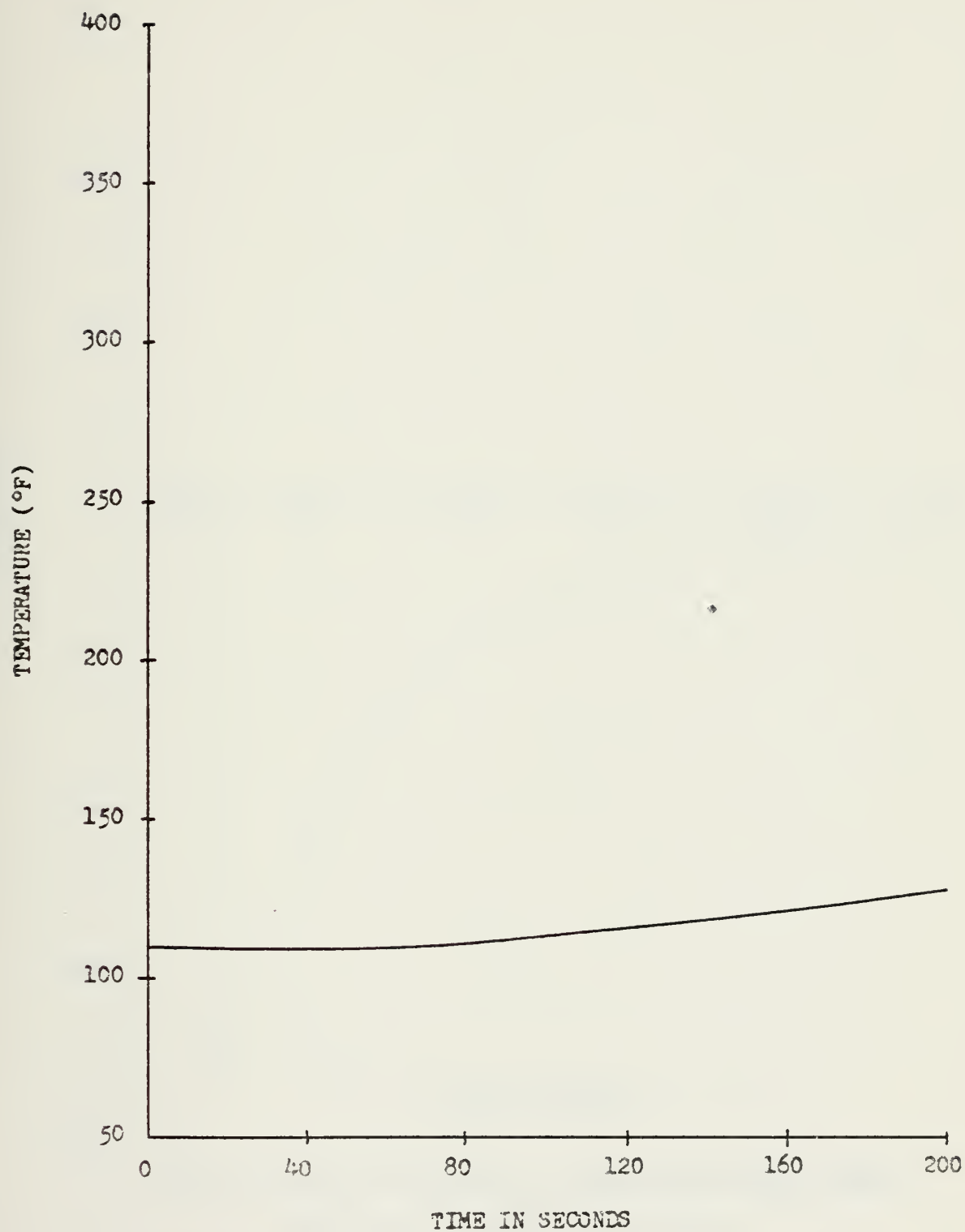


Figure 23- HY 130 SPECIMEN II, TEMPERATURE VERSUS TIME

4.25" from WELD LINE, PASS #2

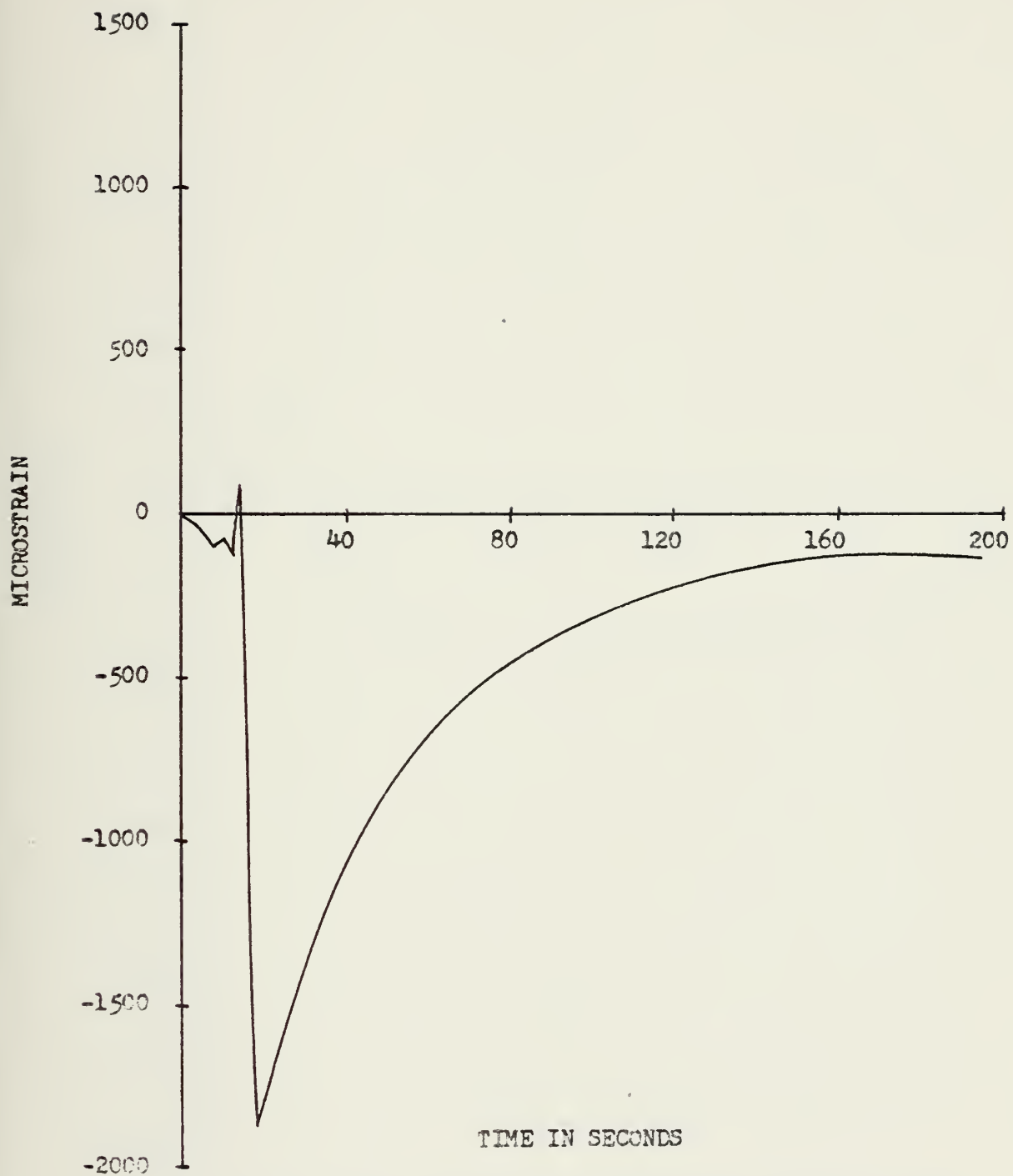


Figure 24- HY 130 SPECIMEN II, LONGITUDINAL STRAIN VERSUS
TIME .50" from WELD LINE, PASS #1

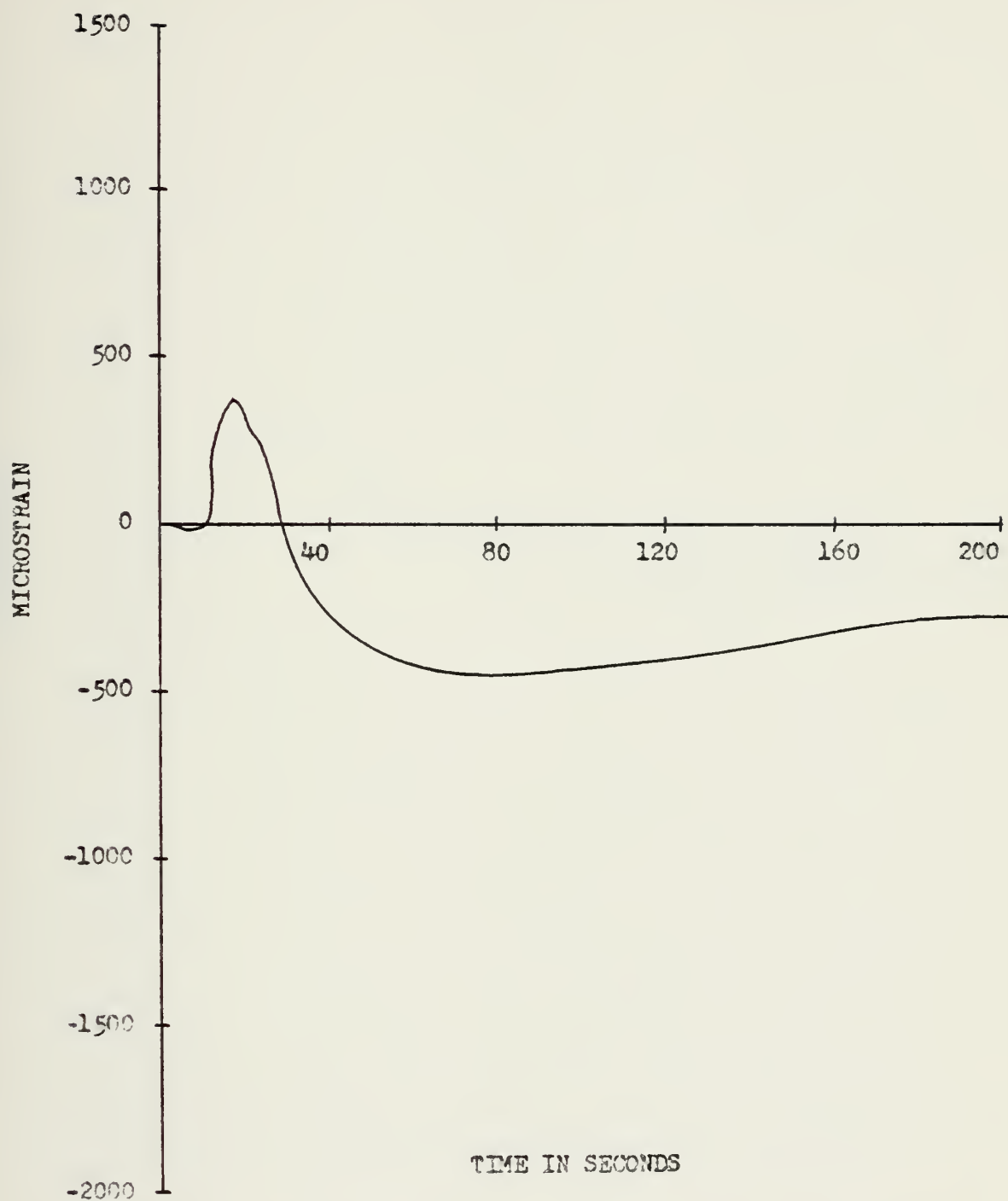


Figure 25- HY 130 SPECIMEN II, LONGITUDINAL STRAIN VERSUS
TIME 1.25" from WELD LINE, PASS #1

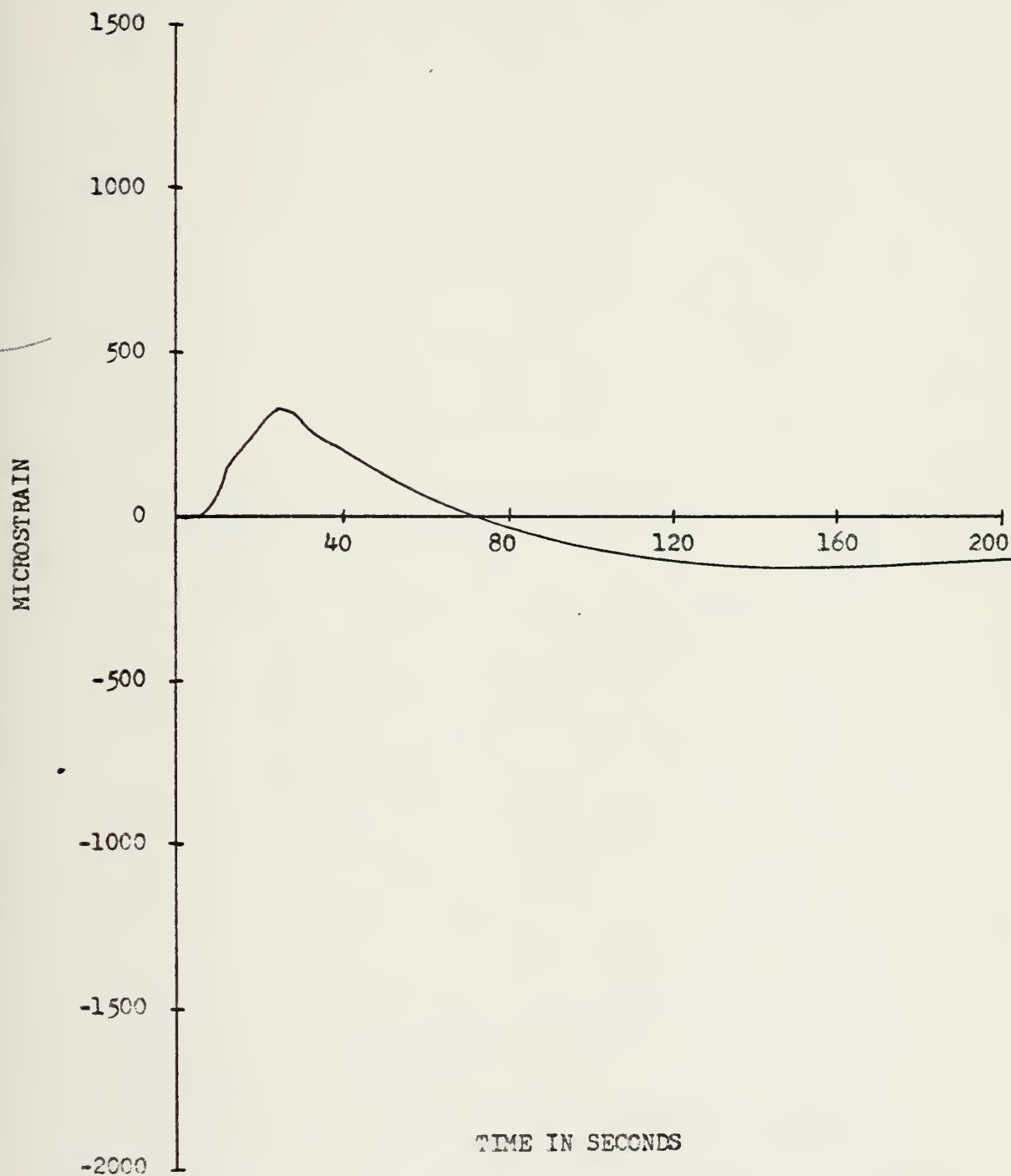


Figure 26- HY 130 SPECIMEN II, LONGITUDINAL STRAIN VERSUS
TIME 2.25" from WELD LINE, PASS #1

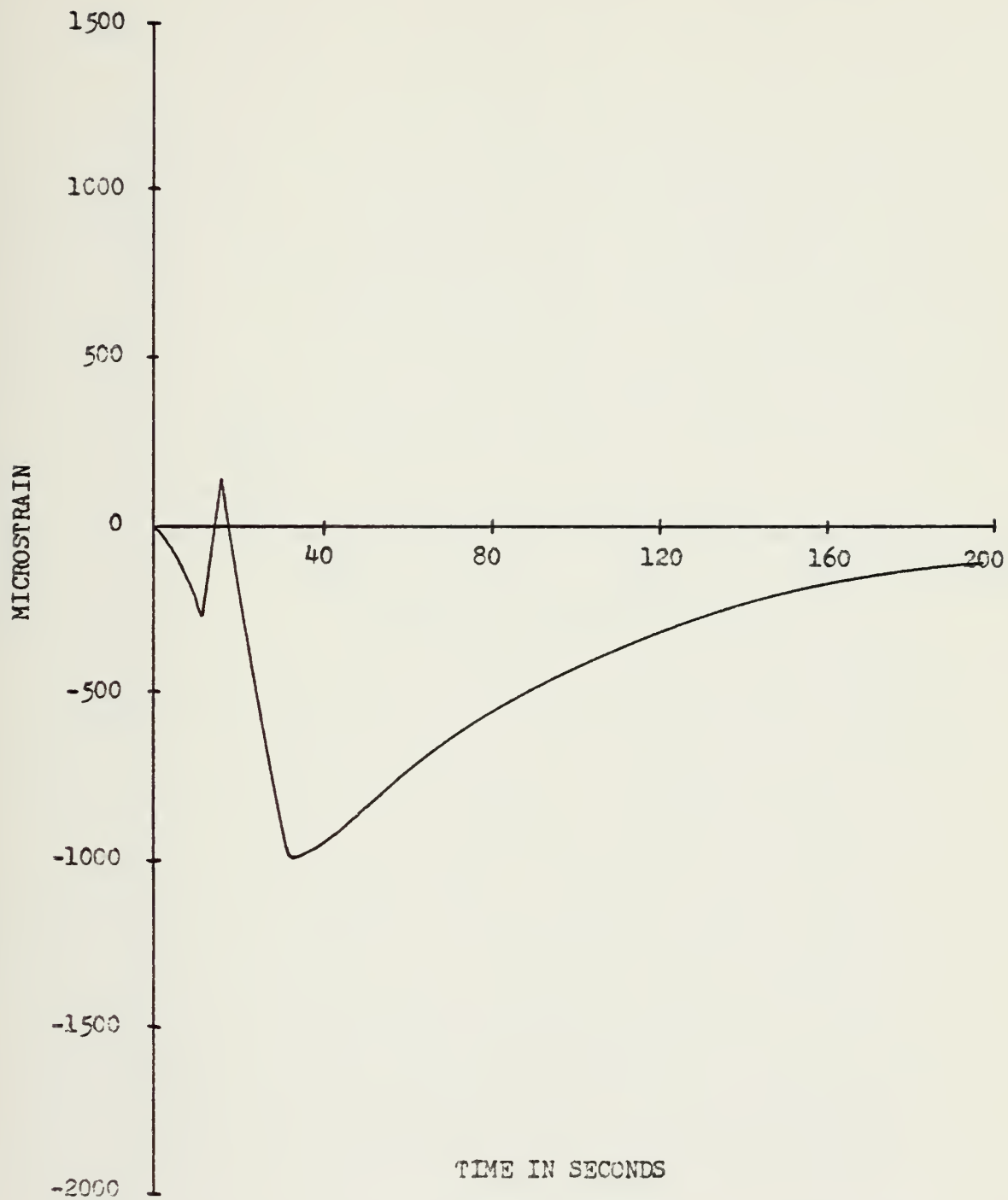


Figure 27- HY 130 SPECIMEN II, LONGITUDINAL STRAIN VERSUS
TIME .50" from WELD LINE, PASS #2

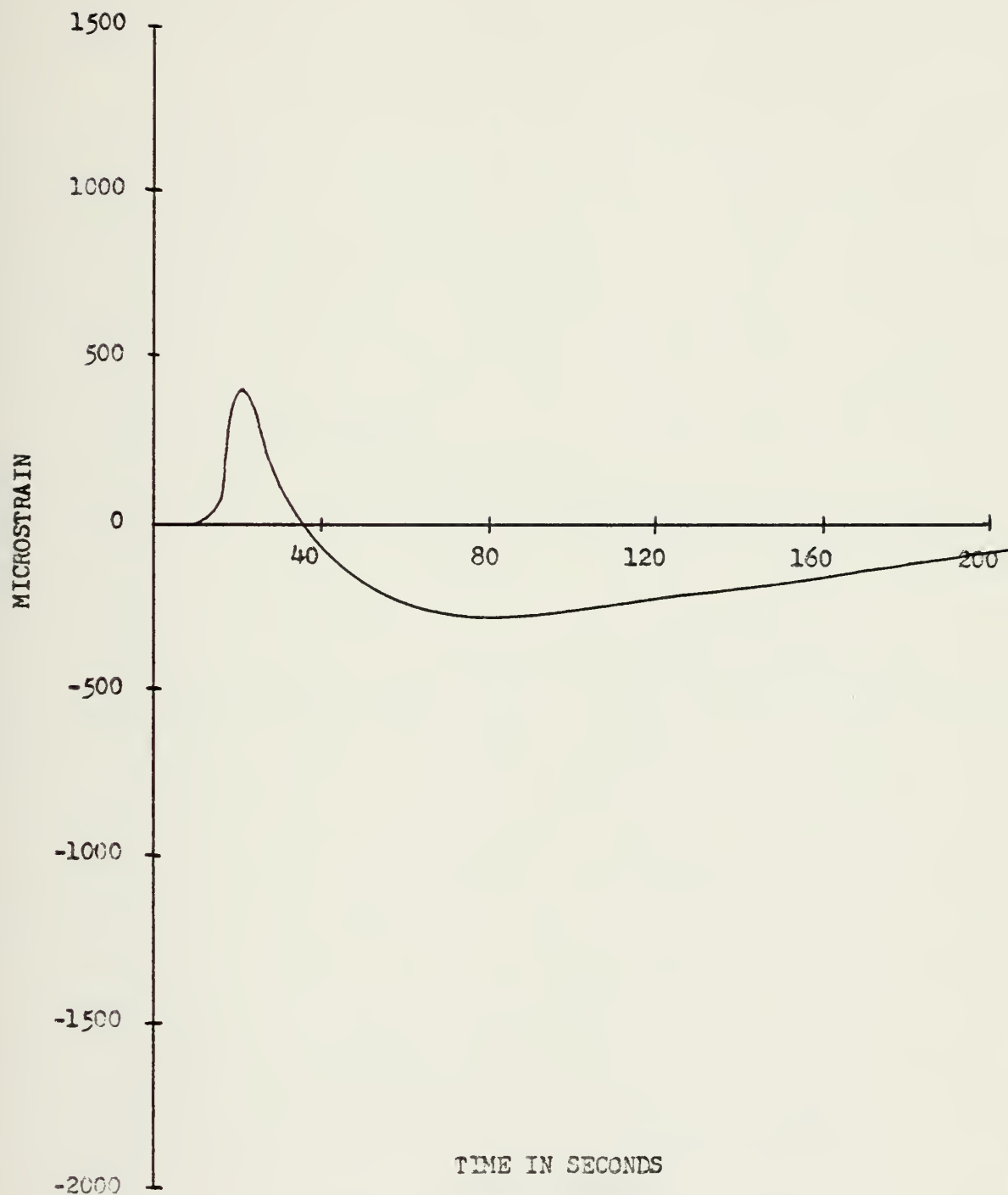


Figure 28- HY 130 SPECIMEN II, LONGITUDINAL STRAIN VERSUS
TIME 1.25" from WELD LINE, PASS #2

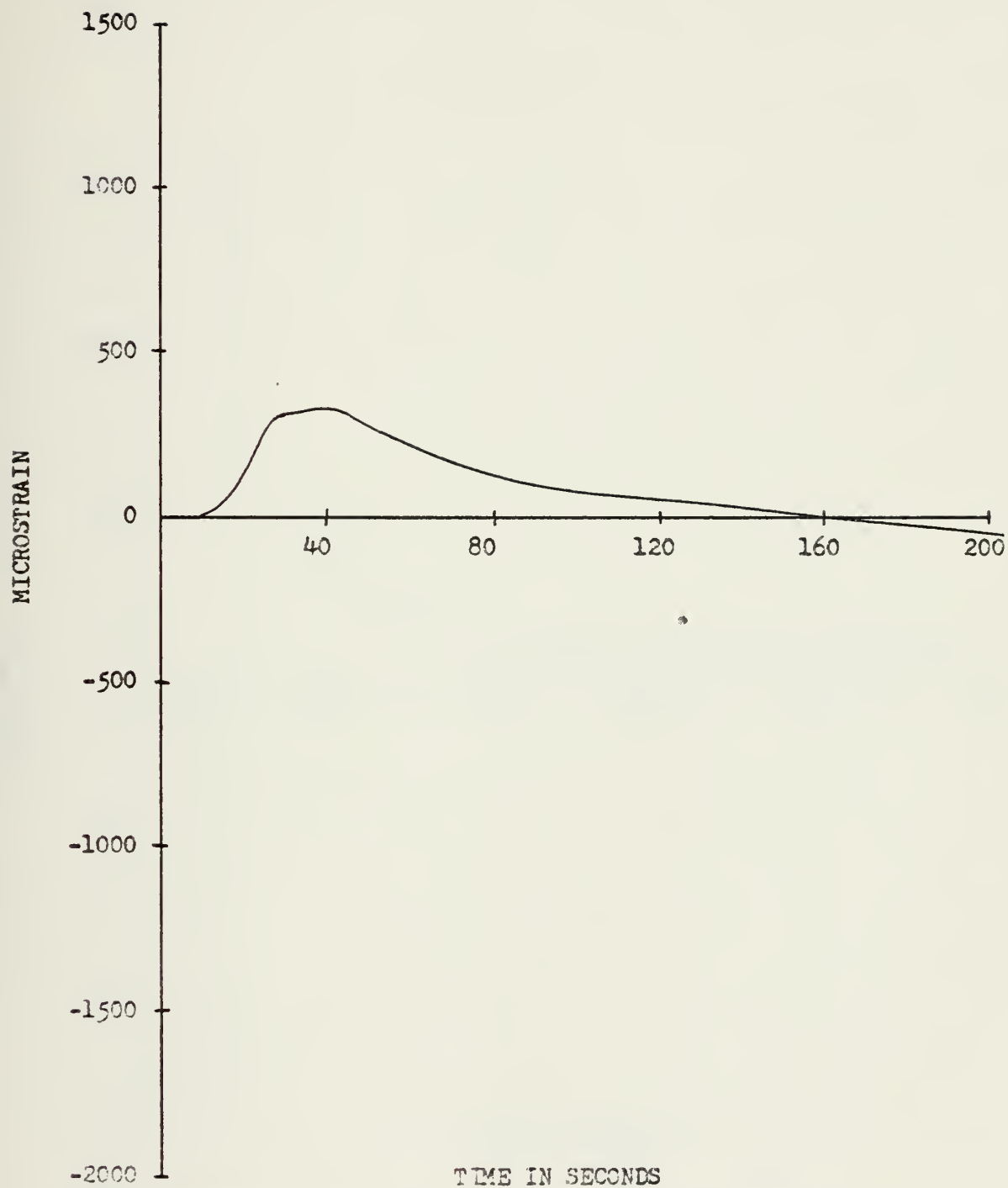


Figure 29- HY 130 SPECIMEN II, LONGITUDINAL STRAIN VERSUS
TIME 2.25" from WELD LINE, PASS #2

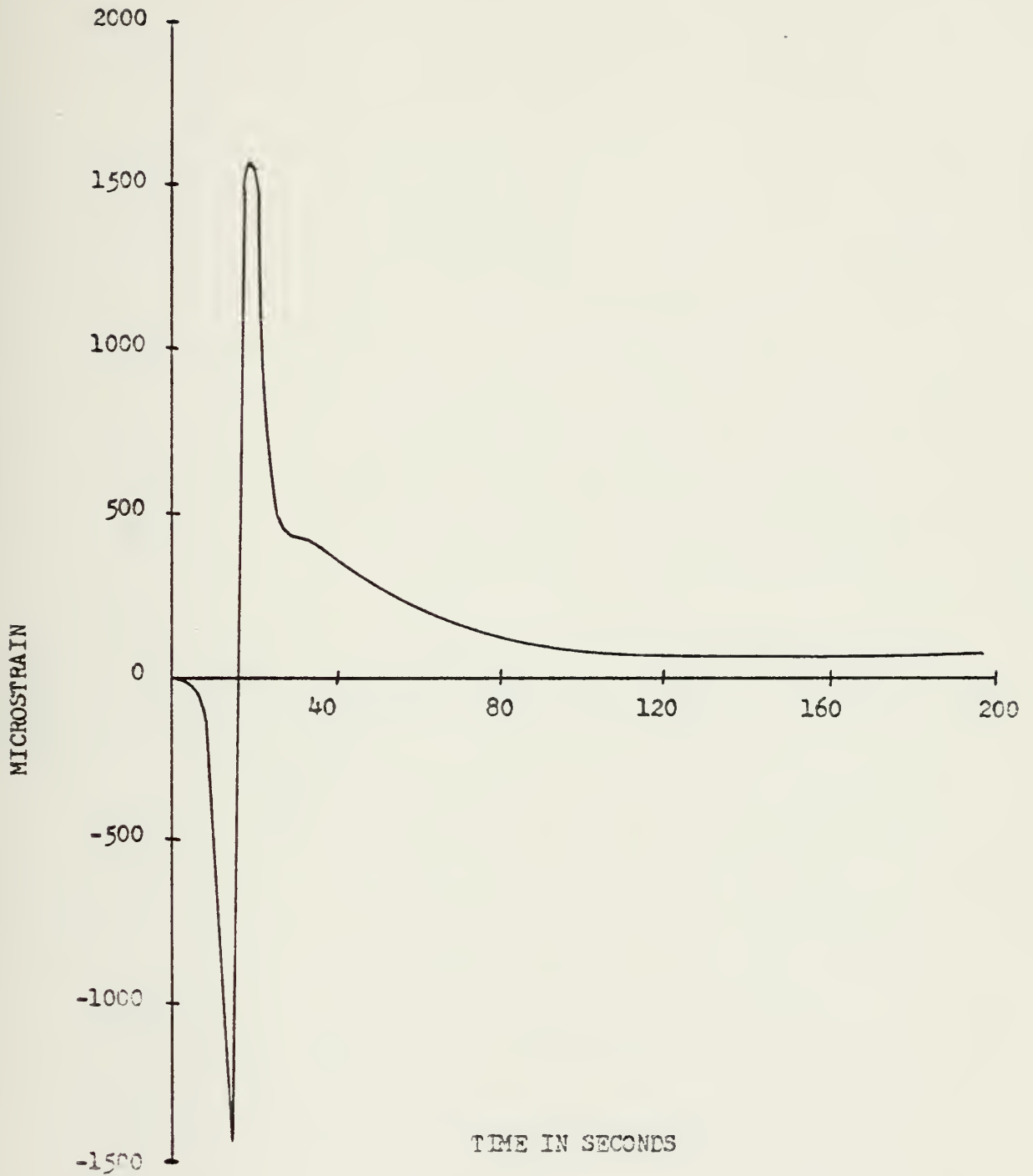


Figure 30- HY 130 SPECIMEN II, TRANSVERSE STRAIN VERSUS
TIME .50" from WELD LINE, PASS #1

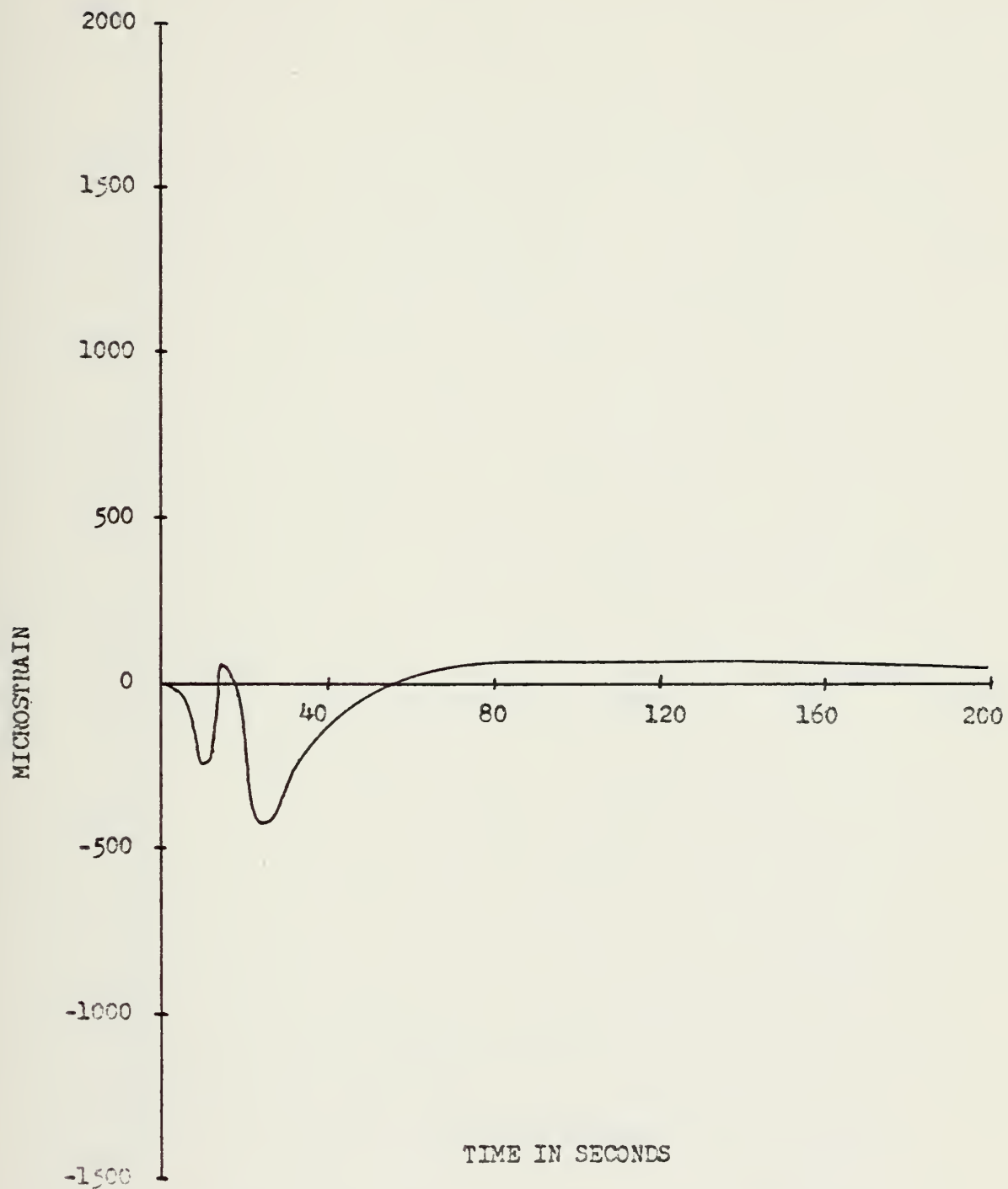


Figure 31- HY 130 SPECIMEN II, TRANSVERSE STRAIN VERSUS
TIME 1.25" from WELD LINE, PASS #1

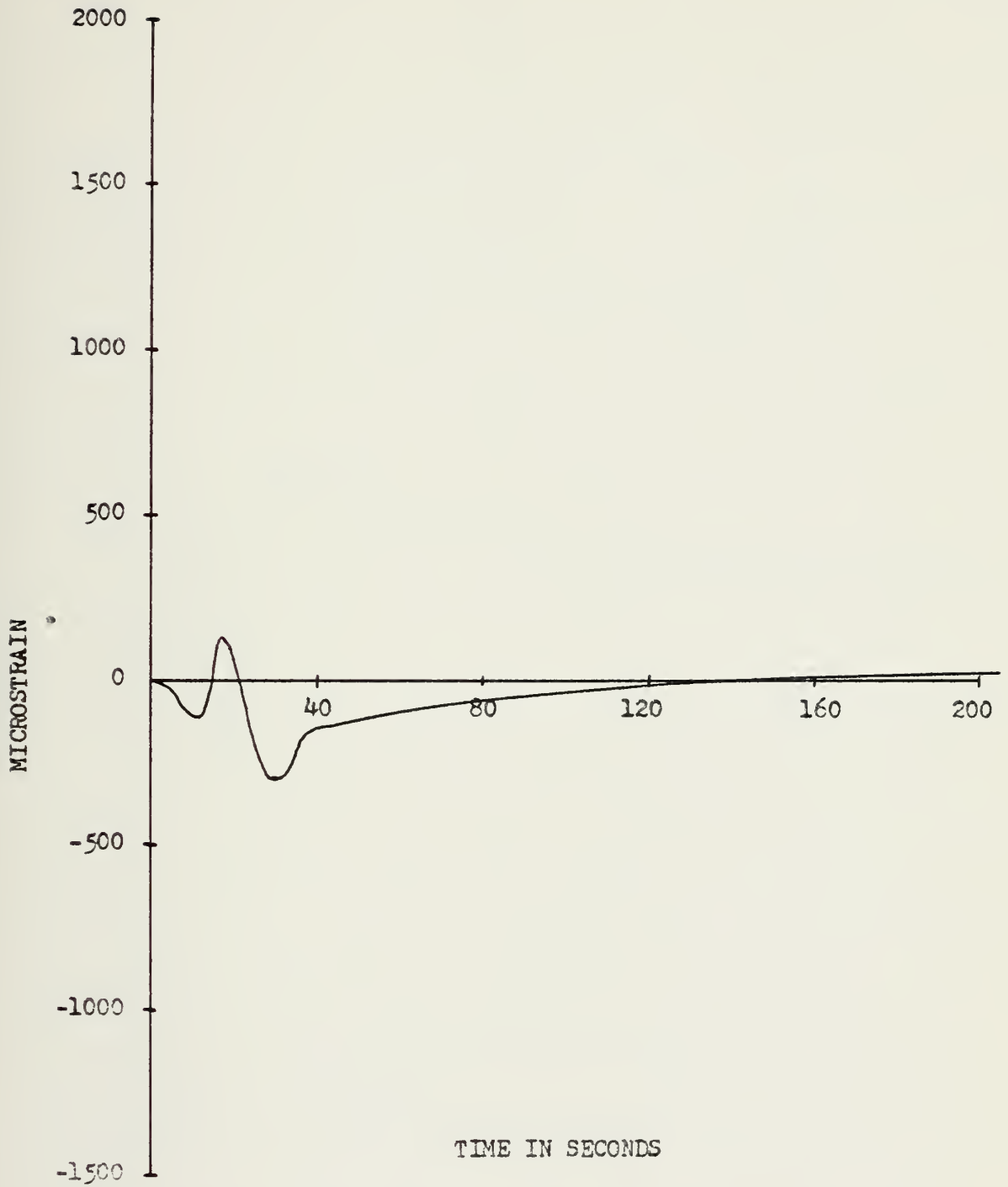


Figure 32- HY 130 SPECIMEN II, TRANSVERSE STRAIN VERSUS
TIME 2.25" from WELD LINE, PASS #1

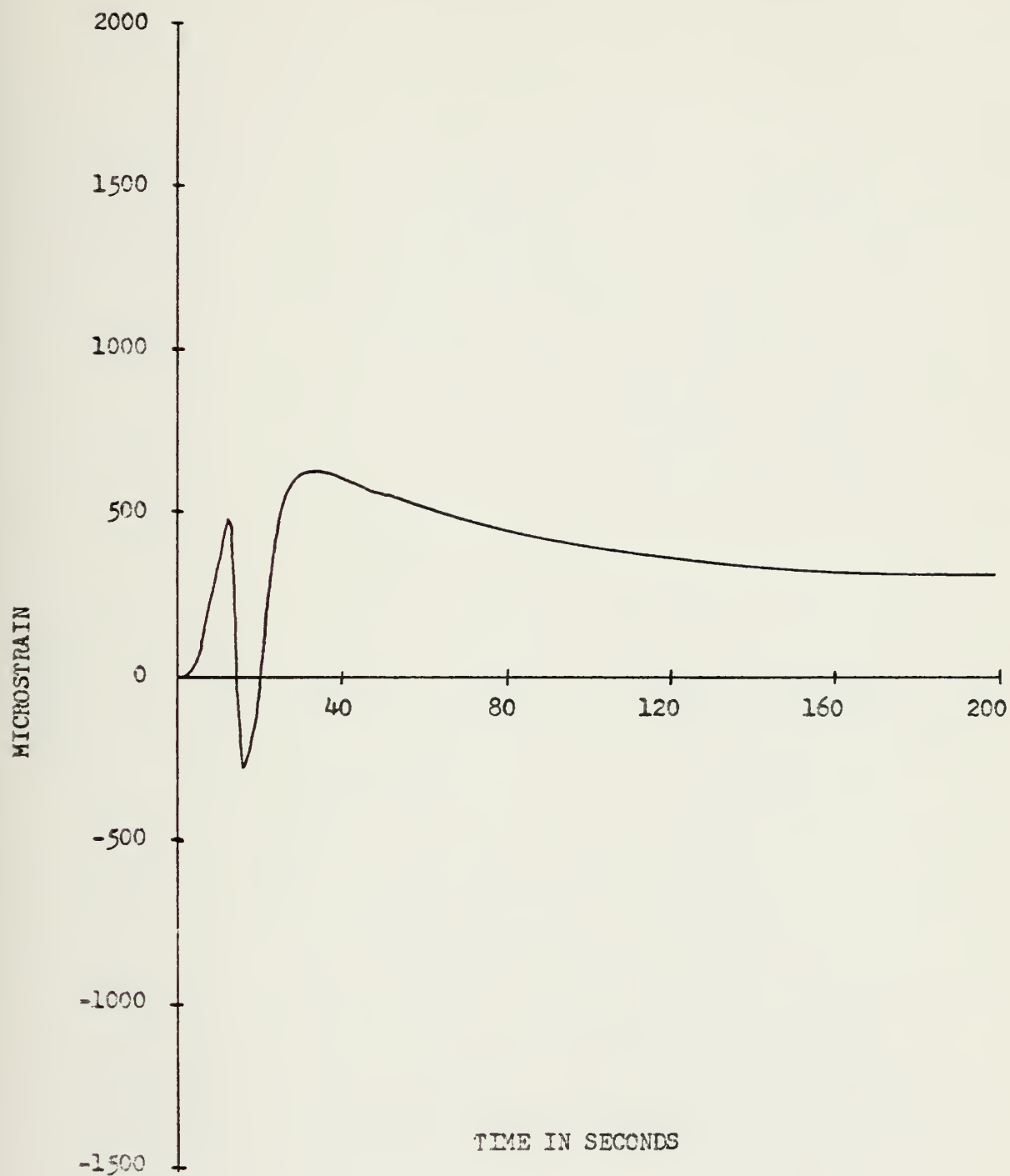


Figure 33- HY 130 SPECIMEN II, TRANSVERSE STRAIN VERSUS
TIME .50" from WELD LINE, PASS #2

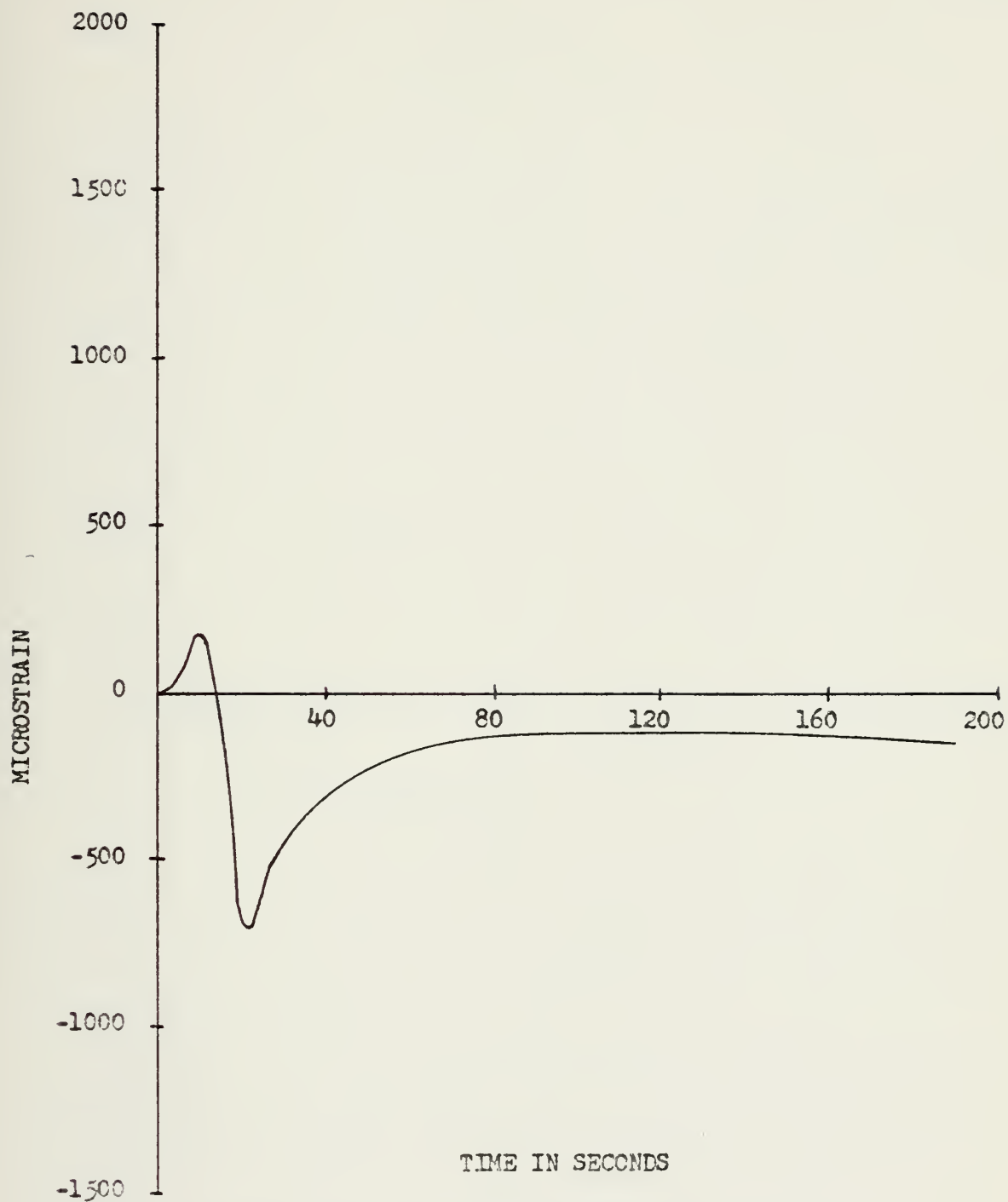


Figure 34- HY 130 SPECIMEN II, TRANSVERSE STRAIN VERSUS
Time 1.25" from WELD LINE, PASS #2

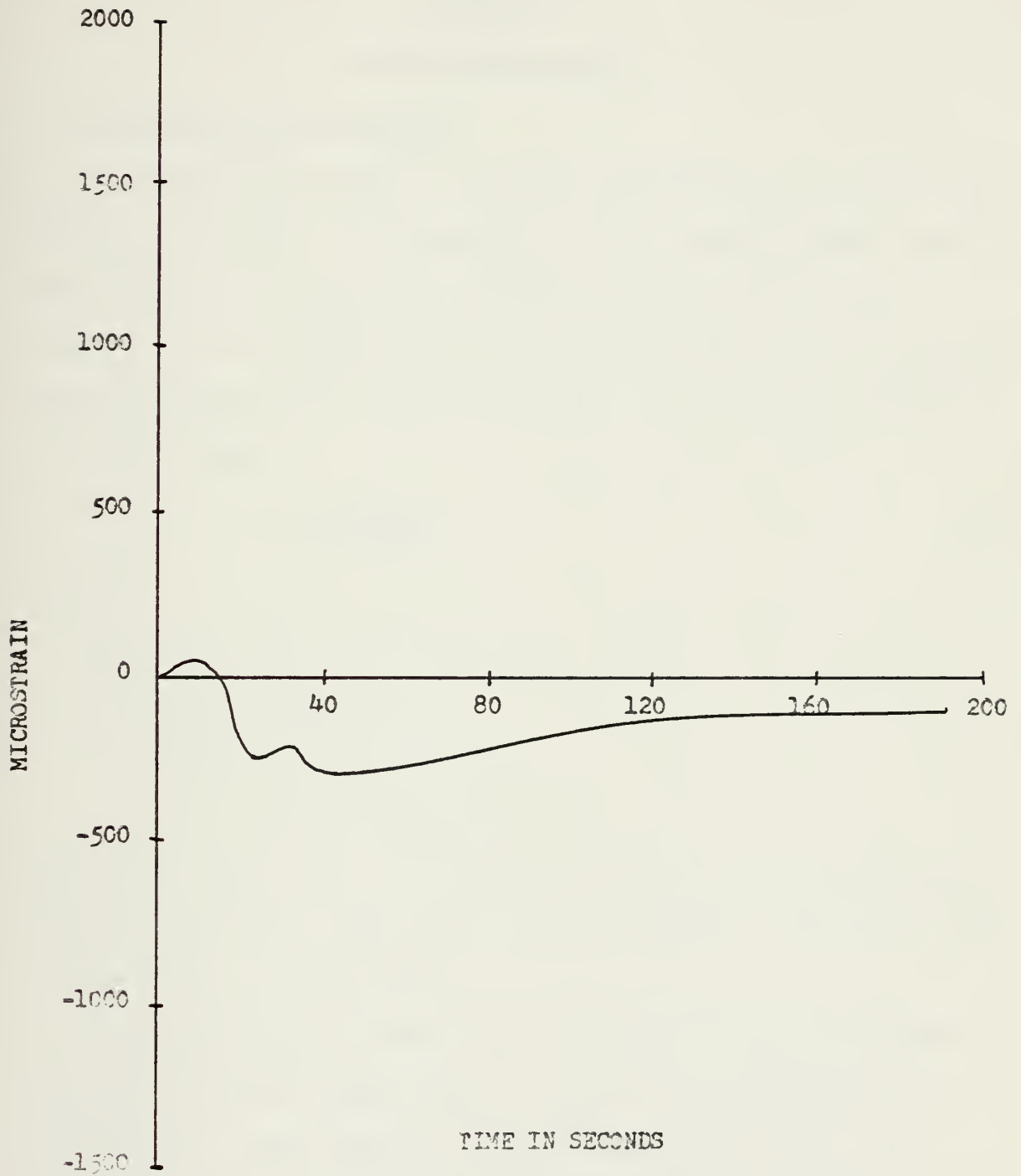


Figure 35- HY 130 SPECIMEN II, TRANSVERSE STRAIN VERSUS
TIME 0.25" from WELD LINE, PASS #2

CHAPTER VII

WELDING COST ANALYSIS

A. Motivation for the Analysis

Currently, arc welding is a widely used process in the fabrication of steel structures. The process is versatile, easy to handle, and in many applications economical. High welding productivity with this process is often achieved by increasing the welding current. As can be seen from Equation (16) however, increasing the current also leads to a higher heat input.

$$KJ = \frac{EI}{V} \frac{60}{1000} \quad (16)$$

where:

KJ = heat input in kilojoules/in

E = Arc voltage in volts

I = Welding current in amperes

V = Arc speed in inches/minute

Higher heat inputs may in turn lead to increased distortion or deterioration of the welds. This is an extremely important consideration when welding higher strength steels.

In order to insure adequate weld strength and fracture toughness with HY-130, the heat input must be limited to approximately 30-40 kilojoules per inch, depending on the plate thickness [34]. This restriction on heat input greatly increases the number of welding passes required to join HY-130 plate in the thicknesses encountered in submarine construction. Table XIII, based on data taken from reference [35],

Table XIIINumber of Welding Passes Required

<u>Steel</u>	<u>Plate Thickness (in)</u>	<u>EBW</u>	<u>GTA</u>	<u>SMA</u>	<u>GMA</u>	<u>SAW</u>
HT-60	4	1	140	80	32	25
HT-90	1.4	1	50	30	25	-
HY-130	1.2	1	48	-	-	-

EBW - Electron Beam Welding

GTA - Gas Tungsten Arc

SMA - Shielded Metal Arc

GMA - Gas Metal Arc

SAW - Submerged Arc Welding

shows the number of welding passes required for various steels, using various welding processes. In addition, welding speeds are also very limited with arc welding of HY-130. The combination of multi-pass welding and relatively low weld metal deposition rates translates directly to increased production man hours and higher costs.

An often expressed disadvantage of using advanced welding processes, such as laser and EB, is the high initial costs of the equipment. Laser and EB welding processes however, possess the potential for welding thick HY-130 plate with only one or two welding passes, and at high welding speeds. In addition, both processes can be utilized without the need for HY-130 filler metal, the cost of which may be substantial. Therefore, with high strength steels, the utilization of laser or electron beam welding processes may be economically feasible. This analysis was motivated by that possibility.

B. Limitations of the Analysis

Admittedly, this analysis did not take into consideration every aspect of submarine construction as it relates to welding. A detailed structural design and production analysis would be an enormous undertaking for a single individual. The economic and technical impacts of adopting laser or EB welding processes would also vary from shipyard to shipyard, depending upon the production techniques used. This analysis therefore focused primarily on the costs directly associated with producing a required amount of welding. Specifically, the factors considered were welding man hours and labor costs, filler metal costs, shielding gas costs, and electrical power consumed.

C. Joint Preparation

The welding requirements as established in Chapters III and IV consisted primarily of pressure hull plating butt welds, and the welds for fabricating the frames and joining them to the pressure hull. Table XIV lists the various welding requirements as a percentage of the total linear feet of welding. It is interesting to note that the frames comprise nearly 90% (in length) of the required welding.

Butt welding with GMA and SMA processes require particular edge preparations. Figure 36 shows the recommended edge preparations for HY-130 butt welds [34]. Since the pressure hull thicknesses exceeds 1.0", the 60° double V joint would be used. The weight of weld metal required for this type of joint is given in Table XV [36].

Fabrication and installation of the frames could be accomplished using fillet welds or T joints. To develop the full strength of a plate, a fillet weld leg would have to be on the order of 75% of the plate thickness. Full strength may also be obtained by double beveling the edge of the plate 45° and spacing the plate so that the root opening is 1/8", allowing for full plate penetration [36]. As compared to a fillet weld, this joint provides for a 25% savings in weld metal for a 1" plate, and 44% for a 4" plate. Therefore, the double bevel joint configuration was chosen for this analysis. The weld joint is shown in Figure 37. The approximate weight of weld metal required for this joint is presented in Table XVI.

Table XIVList of Welding Requirements

<u>Weld</u>	<u>Linear feet</u>	<u>% of Total</u>
Pressure hull circular butt welds	3,409	8.65
Pressure hull seam welds	337	.86
Hemispherical end closures	<u>207</u>	<u>.52</u>
Total Butt Welds	3,953 ft	10.03%
Normal frame web to pressure hull	17,819	45.18
Normal frame web to flange	16,727	42.41
King frame web to pressure hull	515	1.30
King frame web to flange	<u>426</u>	<u>1.08</u>
Total Tee welds	35,487 ft	89.97%
Total linear feet of welding	39,440 ft	

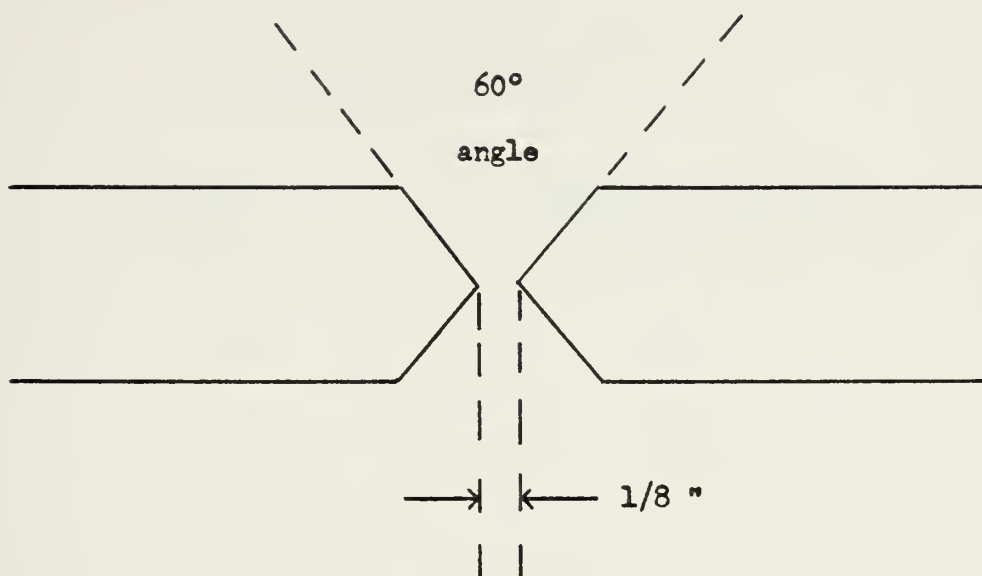


PLATE 1.0 " THICK AND ABOVE

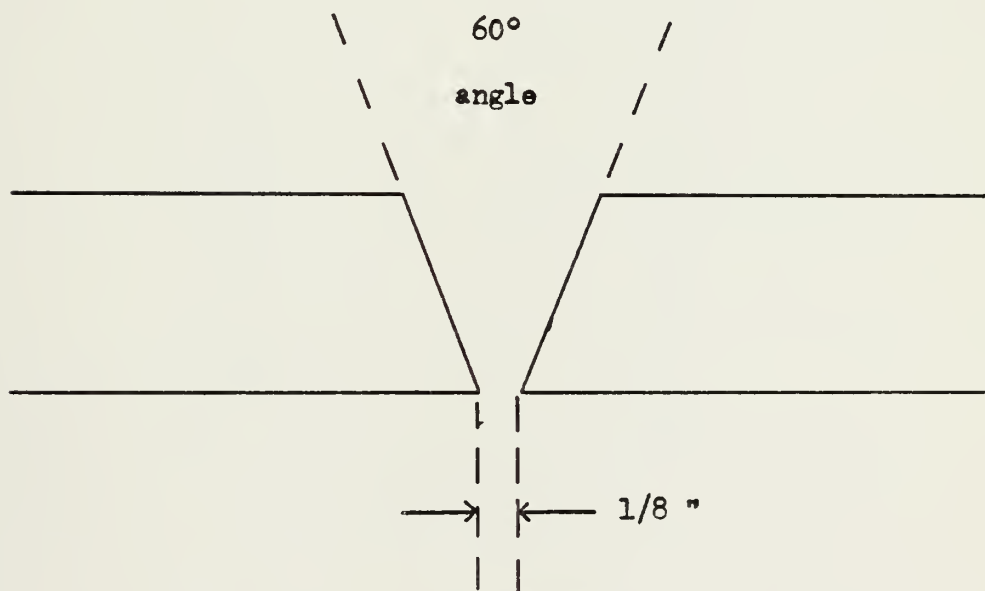


PLATE 1.0 " THICK AND BELOW

Figure 36- EDGE PREPARATIONS FOR HY-130 BUTT WELDS

Table XVWeight of Weld Metal 60° Double VReinforcement: 10% Width of Joint

<u>Plate Thickness (in)</u>	<u>Weight of weld metal (lbs/ft of joint)</u>
1	1.81
1 1/8	2.17
1 1/4	2.61
1 3/8	3.09
1 1/2	3.57
1 5/8	4.12
1 3/4	4.67
2	5.93
2 1/8	6.58
2 1/4	7.32
2 3/8	8.05
2 1/2	8.87
2 5/8	9.67
2 3/4	10.50
3	12.40

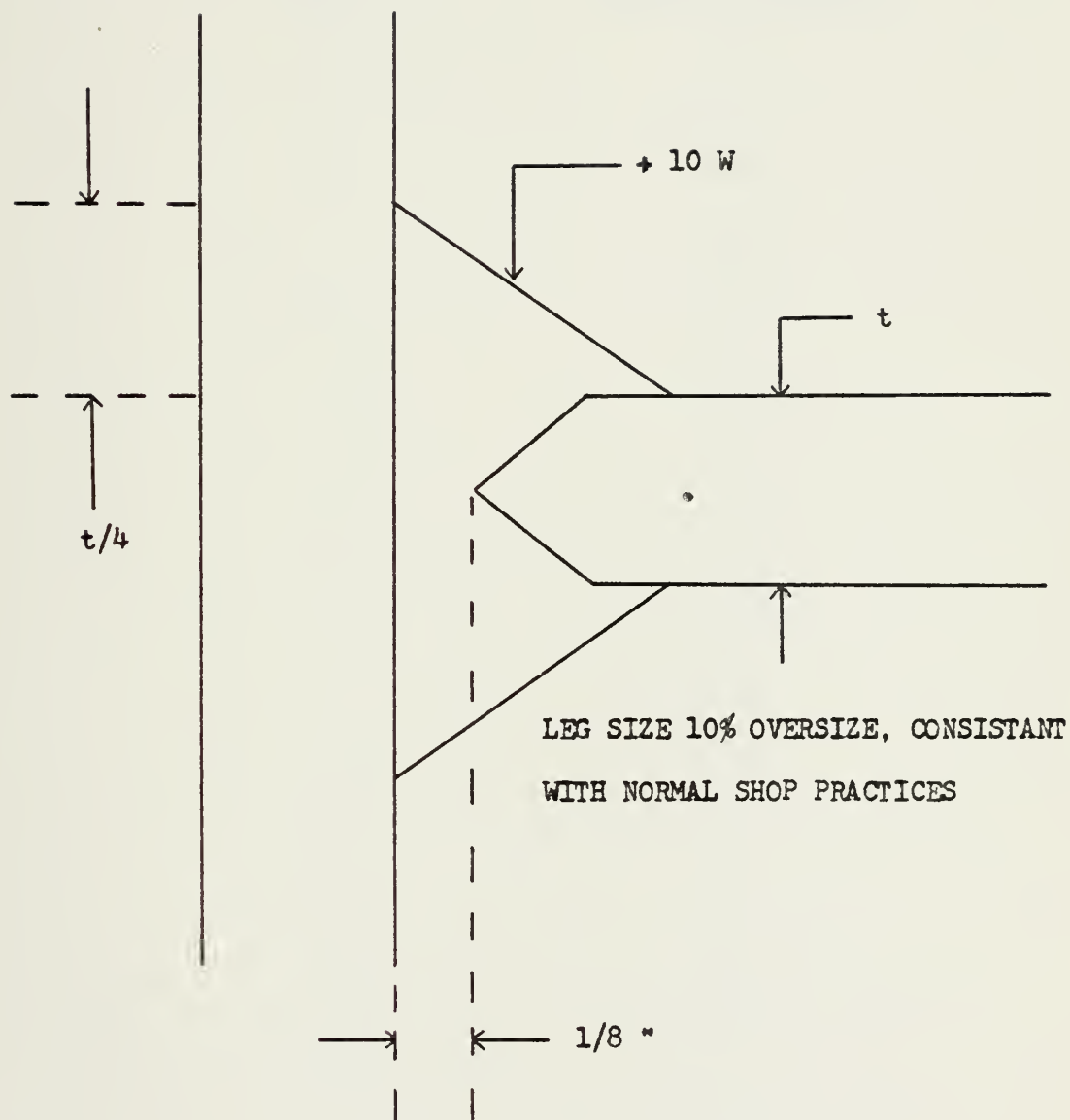


Figure 37- FULL STRENGTH T JOINT

Table XVIFull Strength T Joint

<u>Plate Thickness (in)</u>	<u>Weight of Weld Metal (lbs/ft of joint)</u>
5/8	.854
3/4	1.150
7/8	1.480
1	1.860
1 1/8	2.280
1 1/4	2.740
1 3/8	3.240
1 1/2	3.780
1 5/8	4.360
1 3/4	4.990
2	6.350
2 1/8	7.100
2 1/4	7.800
2 3/8	8.730
2 1/2	9.600
2 5/8	10.500
2 3/4	11.500
3	13.500

D. Filler Metal Requirements

Based on the data in Table XV, 2.61 lbs. of weld metal per foot of weld is required for 1.25" thick HY-130 pressure hull plate butt welding. Table XVI shows that 1.15 lbs/ft is required for each T joint associated with the .75" thick normal frame web, and 3.75 lbs/ft for each joint associated with the 1.5" thick King frame web. Table XVII summarizes the weld metal required. Shielded metal arc and GMA processes would be required that approximately 24 tons of weld metal be deposited. It should be noted that the frames account for nearly 81% of the total weight of filler metal required.

E. Shielded Metal Arc Process

Manual shielded metal arc welding, often referred to as stick electrode welding, is accomplished using flux covered electrodes. Tables XVIII, XIX, and XX list SMA welding procedures used by previous investigators [37, 38, 39]. As can be seen from the data, heat input is generally limited to 30-40 kilojoules per inch. Also, the number of welding passes required become quite high as plate thickness increases. Relatively recent information on HY-130 welding conducted by the Navy is presented in Tables XXI and XXII [40]. The SMA welding parameters used for this economic analysis were in part derived from this data.

1. Weld Metal Deposition Rate

As determined previously, the amount of weld metal required for a pressure hull butt weld was 2.61 lbs/ft. Based on a mean circumference of 103.62 ft, 270.45 lbs of weld metal would be required for a single circular butt weld. The number of welding passes required was estimated

Table XVIIFiller Metal Requirements

<u>Weld</u>	<u>Total Linear feet</u>	<u>Weight of Filler Metal (tons)</u>	<u>% of Total</u>
Pressure hull butt welds	3,953	4.61	19.3
Normal Frames	34,546	17.74	74.1
King Frames	941	1.59	6.6
Total	39,440	23.94	100

One long ton = 2240 lbs.

Table XVIIISMA Welding Procedures for HY-130 Butt Welds

<u>Welding Parameter</u>	<u>Specification</u>
Electrode	* M14018
Electrode diameter (in)	5/32, 3/16
Current (amps)	150 - 210
Voltage (volts)	22
Preheat temperature (°F)	200
Interpass temperature (°F)	200
Maximum heat input (KH/in)	37.5
Arc travel speed (IPM)	6-8
Joint geometry	Double V 60° included angle

* Manufactured by the McKay Company.

Table XIXRecommended SMA Procedures for Welding HY-130

<u>Plate Thickness (in)</u>	<u>Preheat and Interpass Temp. (°F)</u>	<u>Heat Input (KJ/in)</u>
Less than 3/8	not recommended	
3/8 including 5/8	126-151	30
Over 5/8 and including 7/8	151-200	35
Over 7/8 and including 1 1/4	200-275	35
Over 1 1/4 and including 4	225-300	40

Table XXSMA Welding Parameters for Welding HY-130 in the Flat Position

<u>Plate Thickness (in)</u>	<u>Electrode Diameter (in)</u>	<u>Voltage (volts)</u>	<u>Current (amps)</u>	<u>Travel Speed (IPM)</u>	<u>Number of passes</u>
1/4	5/32	22.5	160	8-10	4-5
5/16	5/32	22.5	160	8-10	4-5
3/8	5/32	22.5	160	8-10	4-6
1/2	5/32	22.5	160	8-10	6-7
3/4	5/32	22.5	160	8-10	14-16

Table XXISMA Welding Conditions for 1/4" Thick HY-130

Joint	60° V groove, 1/8" gap
Position	Flat
Filler Metal	E14018, 5/32" diameter electrode
Amperage (amps)	125 DCRP
Voltage (volts)	25 - 30
Passes	3
Travel Speed (IPM)	8.9 - 10.1
Environment	gas + flux covering
Preheat Temp (°F)	248
Interpass Temp (°F)	203 - 302
Heat Input (KJ/in)	20.25 - 23.25

Table XXIISMA Welding Conditions for 1/2" Thick HY-130

Joint	60° V groove, 1/8" gap
Position	Flat
Filler Metal	E14018, 5/32" Diameter electrode
Amperage (amps)	125 DCRP
Voltage (volts)	25 - 30
Passes	7
Travel Speed (IPM)	7
Environment	Gas + flux covering
Preheat Temp (°F)	248
Interpass Temp (°F)	203 - 302
Heat Input (KJ/in)	27.5 - 29.5

to be 24 to 27 passes. With an assumed welding speed of 6 inches per minute, the weld metal deposition rate was calculated to be 2.9 to 3.2 lbs/hour. For the purpose of this analysis, a SMA deposition rate of 3.0 lbs/hour was assumed to be a representative value. Table XXIII summarizes the SMA welding parameters selected for the economic analysis. Welding speeds were calculated from the heat input equation.

2. Welding Man-Hours and Costs

The number of arc hours required to deposit 24 tons of weld metal was determined from the deposition rate of 3.0 lbs/hr.

$$H_{\text{arc}} = \frac{W_r}{D} \quad (17)$$

where

H_{arc} = hours of actual arc time required

W_r = weight of weld metal required, lbs.

D = deposition rate, lbs/hr

The number of arc hours computed using Equation (17) was 17,920 hours. However, in order to estimate the actual welding man-hours required, an operating factor (OF) must be applied to the arc hours. The operating factor takes into consideration the down time between electrodes, including the time required to lift up the helmet, clean the slag off the weld, insert a new electrode into the holder, etc. The operating factor also takes into consideration the time the welder spends on coffee breaks, personal business at work, and training. Values of OF ususally range from .2 to .6, but may be higher for automated welding, or lower for construction field welding [41].

Table XXIIISelected Welding Parameters for HY-130 SMA Welding

<u>Plate Thickness (in)</u>	<u>Maximum Heat Input (KJ/in)</u>	<u>Deposition Rate (Lbs/hr)</u>	<u>Welding Speed (IPM)</u>
3/4	35	3.0	6.4
1 1/4	37.5	3.0	6.0
1 1/2	37.5	3.0	6.0

Welding Current - 125 amps DCRP

Voltage - 30 volts

Electrode - E14018, 5/32" diameter

Choosing the proper value for the operating factor is important since it has such a significant impact on cost. Unfortunately, obtaining production rates from commercial shipyards is difficult since they are kept confidential due to the competitiveness of the bidding process. Submarine welding is also very specialized welding, requiring stringent welder qualifications and non-destructive testing procedures. As much as 50% of a welders time can be spent in training for new qualifications, or for maintaining his current qualifications [42]. Therefore, the value of the operating factor appears to be on the low end of the usual range. An OF of .30 was assumed for this analysis. Actual man-hours were calculated from Equation (18).

$$M_h = \frac{H_{\text{arc}}}{\text{OF}} \quad (18)$$

where

M_h = actual welder man-hours

H_{arc} = arc hours

OF = operating factor

The welding man-hours were calculated to be 59,734 hours.

The cost of labor must take into consideration hourly wages, benefits, overhead, and profits. A recent value of labor and overhead costs for the Charleston Naval Shipyard was determined to be \$200 per 8 hour man day, or \$25/hr [42]. Table XXIV summarized corresponding data and remarks for commercial shipyards [43]. A good representative value for submarine welding labor and overhead costs appeared to be \$25/hr. The labor and overhead costs were therefore calculated to be \$1,493,350.

Table XXIVU.S. Hourly Costs of Welder

	1	2	3	4	5
<u>Shipyard</u>	<u>Base pay/hr</u>	<u>Benefits</u> <u>26% of 1</u>	<u>Overhead</u> <u>65% of 1</u>	<u>Profits</u> <u>10% of 1,2, & 3</u>	<u>TOTAL</u>
A	\$10.20	\$2.65	\$6.63	\$1.94	\$21.92
B	8.98	2.33	6.73	1.80	19.84
C	7.90	2.05	5.92	1.59	17.46

The above are average costs of welders in U.S. shipbuilding yards. Benefits are fairly uniform, but overhead varies from about 52% to over 78% of base pay. A cost of \$200 per day for a welder of specialized steels appears appropriate.

3. Electrical Power and Costs

Table XXV shows typical electrical efficiencies for various welding equipment [44]. Arc power for the SMA welding parameters chosen was 3.75 KW. Assuming an electrical efficiency of .65, 5.77 KW of power would be required while welding. Based on 17,920 hours of arc time, 103,398.4 KWH would be consumed. Electrical costs for August 1978 were \$.0375 per KWH [44]. Corrected for 10% inflation, the assumed current cost was calculated to be \$.04125 per KWH. Total electrical costs were therefore calculated to be \$4,265. It should be noted that the no load power consumption was neglected, but in reality would add to the electrical costs.

4. Filler Metal Costs

With SMA welding, considerably more electrode consumption occurs than might be expected. In addition to determining the amount of weld metal deposited, compensation must also be made for loss of electrode material as shielding gas, slag, and splatter. Typical values of deposition efficiency are presented in Table XXVI [41]. The efficiency given for stick electrodes does not take into account the stub which is thrown away. This length of stub can vary from 2 to 4 inches, depending on joint configuration and shop practices. This analysis assumed a 2 inch stub, and a 5/32" diameter electrode length of 14". Therefore, 14.3% of each electrode would also be lost due to the unusable stub. The overall deposition efficiency was then calculated to be 50.7%. In order to deposit 24 tons of weld metal, 47.34 tons of electrode would be consumed. The total number of 14" long electrodes

Table XXVElectrical Efficiencies

d.c. welding generators	45% - 60%
a.c. generator	65% - 70%
Welding rectifiers	65% - 75%
Welding transformers	75% - 85%

Table XXVIDeposition Efficiencies

Stick-electrode welding	0.65
Self-shielded flux-cored welding	0.82
Gas metal-arc welding	0.92
Submerged-arc welding	1.00

required would be approximately 505,344 electrodes. Current costs of E14018, 5/32" diameter electrodes was determined to be \$3.28/lb [45]. The total cost for the filler metal was calculated to be \$347,816.

A summary of the factors considered in the SMA economic analysis are presented in Table XXVII.

F. Gas Metal Arc Process

Gas metal arc welding uses a continuous electrode wire for the filler metal, and an externally supplied gas for shielding. The process is either semiautomatic, using a handheld gun to which the wire is fed automatically, or fully automatic. Tables XXVIII, XXIX, and XXX list GMA welding procedures used by previous investigators [37, 38, 39]. The heat inputs are comparable to those for SMA welding. Tables XXXI and XXXII show the GMA welding procedures used by the Navy during testing of HY-130 welding [40]. The GMA welding parameters used for this economic analysis were derived from this data.

1. Weld Metal Deposition Rate

The wire feed speed used during the Navy testing was 210 IPM. Calculations indicated that the weld metal deposition rate at this wire feed speed was 10 lbs/hr if a deposition efficiency of .92 is assumed. This value corresponds to Figure 38, based on data presented in Reference [41]. Therefore, a GMA deposition of 10 lbs/hr was assumed for this analysis. Table XXXIII summarizes the GMA welding parameters selected for the economic analysis. Welding speeds were calculated from the heat input equation.

Table XXVIISummary of SMA Welding Parameters and Costs

Weld metal deposited	24 tons
Electrode	E14018, 5/32" diameter
Welding current	125 amps DCRP
Voltage	30 volts
Deposition rate	3.0 lbs/hr
Operating Factor	.30
Welding Man-hours	59,734
Electrical Power Consumed	103,398.4 KWH
Electrode required	47.34 tons
Labor and Overhead	\$25/hr.
Electrical Power	\$.04125 per KWH
Filler Metal	\$3.28 per lb.
Labor and Overhead costs	\$1,493,350
Electrical costs	\$4,265
Filler Metal Costs	\$347,816
Total Costs	\$1,845,431

Table XXVIIIGMA Welding Procedures for HY-130 Butt Welds

<u>Welding parameter</u>	<u>Specification</u>
Electrode	* L140
Electrode diameter (in)	1/16
Current (amps)	285 - 330
Voltage (volts)	28 - 29
Preheat Temp. (°F)	225
Interpass Temp. (°F)	225
Maximum heat input (KJ/in)	45
Arc travel speed (IPM)	13 - 14
Joint geometry	Double V 60° included angle
Shielding gas	Argon - 2% O ₂

Table XXIXRecommend GMA Procedures for Welding HY-130

<u>Plate Thickness</u> <u>(in)</u>	<u>Preheat and</u> <u>Interpass Temp.</u> <u>(°F)</u>	<u>Heat Input</u> <u>(KJ/in)</u>
Up to 3/8	not recommended	
3/8 and including 5/8	126 - 151	35
Over 5/8 and including 7/8	151 - 200	40
Over 7/8 and including 1 1/2	200 - 275	45
Over 1 1/2	225 - 300	50

Table XXXGMA Welding Parameters for Welding HY-130 in the
Flat Position

<u>Plate Thickness (in)</u>	<u>Electrode Diameter (in)</u>	<u>Voltage (volts)</u>	<u>Current (amps)</u>	<u>Travel Speed (IPM)</u>	<u>Number of passes</u>
1/4	.045	25.5	220	11	2
3/8	.045	26.0	270	10	2
1/2	.045	25.0	270	12	4
3/4	.045	26.0	270	10-14	10-11

Shielding gas - 98% Argon/2% O₂

Table XXXIGMA Welding Conditions for 1/4" Thick HY-130

Joint	60° V groove, 1/8" gap
Position	Flat
Filler Metal	140S, 1/16" diameter
Amperage (amps)	300 DCRP
Voltage (volts)	22.5 - 24.0
Passes	3
Travel Speed (IPM)	21 - 23
Wire Feed (IPM)	210
Environment	Argon + 2% O ₂
Preheat Temp (°F)	248
Interpass Temp. (°F)	203-302
Heat Input (KJ/in)	19.55

Table XXXIIGMA Welding Conditions for 1/2" Thick HY-130

Joint	60° V groove, 1/8" gap
Position	Flat
Filler Metal	140S, 1/16" diameter
Amperage (amps)	300 DCRP
Voltage (volts)	23.5 - 24.5
Passes	5
Travel Speed (IPM)	14 - 15
Wire Feed (IPM)	210
Environment	Argon + 2% O ₂
Preheat Temp (°F)	248
Interpass Temp (°F)	203 - 302
Heat Input (KJ/in)	28.95 - 29.97

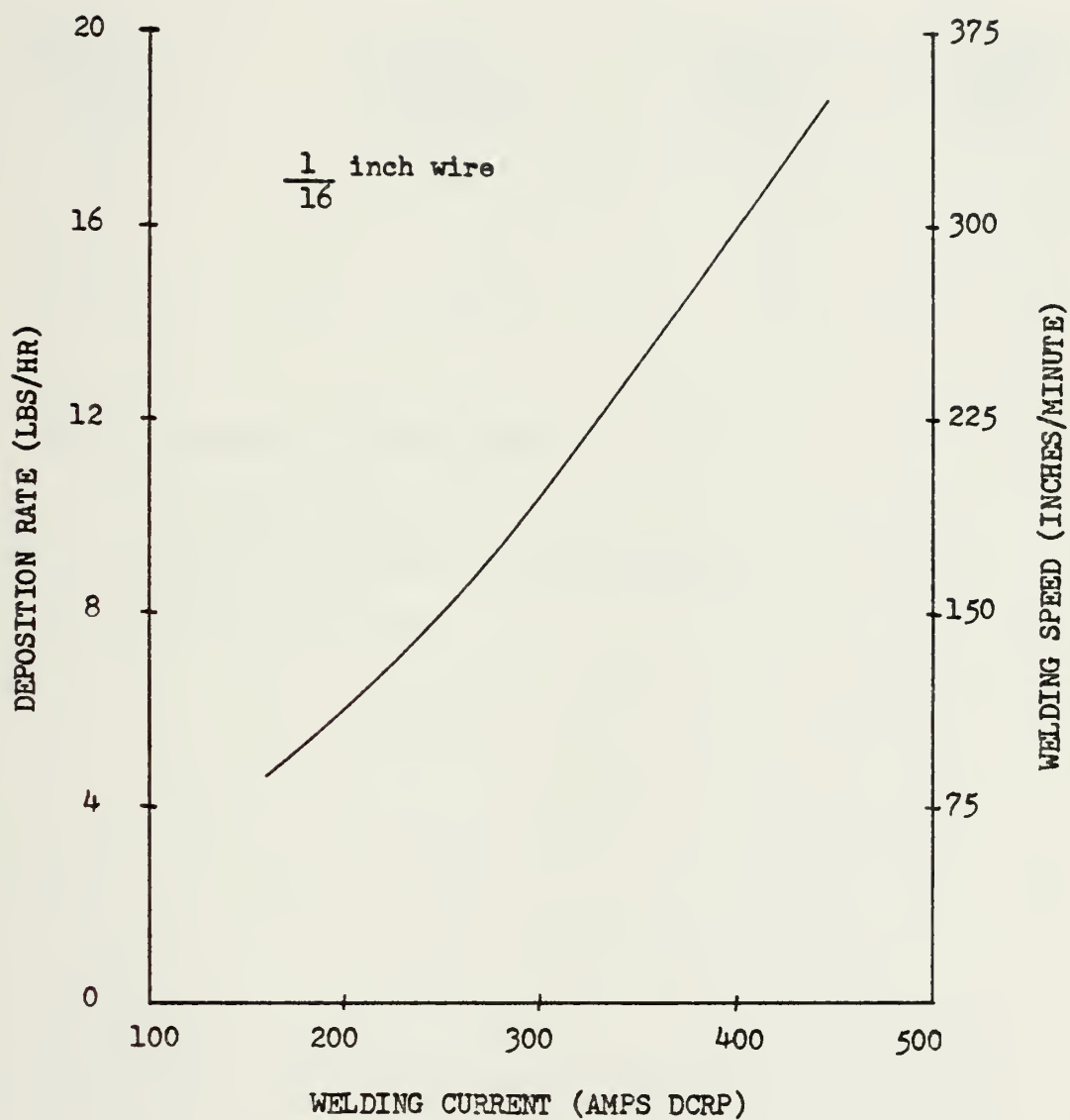


Figure 38- GMA DEPOSITION RATES

Table XXXIIISelected Welding Parameters for HY-130 GMA Welding

<u>Plate Thickness (in)</u>	<u>Maximum Heat Input (KJ/in)</u>	<u>Deposition Rate (Lbs/hr)</u>	<u>Welding Speed (IPM)</u>
3/4	35	10.0	12.3
1 1/4	37.5	10.0	11.5
1 1/2	37.5	10.0	11.5

Welding Current - 300 Amps DCRP

Voltage - 24 volts

Electrode - L140 wire, 1/16" diameter

Wire Feed - 210 IPM

2. Welding Man-hours and Costs

The number of arc hours required was determined in the same manner as for SMA welding using Equation (17). The number of arc hours calculated was 5,376 hours based on a deposition rate of 10 lbs/hr. An assumed operating factor of .40 was assigned to semiautomatic GMA welding. The total welding manhours required were therefore calculated to be 13,440 hours. The labor and overhead costs were in turn calculated to be \$336,000 based on \$25/hr.

3. Electrical Power and Costs

Arc power for the GMA welding parameters chosen is 7.20 KW. Assuming an electrical efficiency of .65, 11.08 KW of power would be required while welding. Based on 5,376 hours of arc time, 59,566 KWH would be consumed. At \$.04125 per KWH, the cost of electricity was calculated to be \$2,457. As with SMA, no load power consumption was neglected.

4. Filler Metal Costs

The deposition efficiency for GMA welding was assumed to be .92. In order to deposit 24 tons of weld metal, 26.1 tons of electrode would be consumed. Current costs of L 140, 1/16" diameter, electrode wire was determined to be \$7.36 per lb [45]. The total cost for the filler metal was calculated to be \$430,295.

5. Shielding Gas Costs

Shielding gas flow rate for GMA welding usually varies from 40 to 60 CFH [41]. A flow rate of 50 CFH of Argon + 2% O₂ was assumed for this analysis. Based on 5,376 hours of arc time, the total amount of gas

required was computed to be 268,000 ft³. The current cost of Argon + 2% O₂ was determined to be \$.0696 per ft³ [46]. The cost of shielding gas was calculated to be \$18,708.

A summary of the factors considered in GMA welding are presented in Table XXXIV.

G. Laser Welding Process

The laser welding parameters chosen for this analysis were based on the experimental welding carried out by this author, and as outlined in Chapter V and VI. The welding parameters are summarized in Table XXXV.

1. Welding Man-hours and Costs

Pressure hull welding and King Frame installation would necessitate 2 welding passes per welding joint with 12 KW of beam power. As previously calculated; these joints amounted to 4,894 linear feet of welding. At a welding speed of 30 IPM, and with 2 pass welding, 65.25 hours of welding time would be required to complete these welds. The normal frames were assumed to be welded with one welding pass and 12 KW of beam power. The normal frames account for the 34,546 linear ft. of remaining welding. At a welding speed of 30 IPM, and with 1 pass welding, 230.31 hours of welding would be required to complete the normal frames. The total actual required welding time was therefore calculated to be 295.56 hours. These hours represent laser beam hours, the equivalent of arc hours for SMA or GMA welding.

Laser welding is a highly automated method of welding. The operating factor would therefore probably be quite high. For the

Table XXXIVSummary of GMA Welding Parameters and Costs

Weld Metal Deposited	24 tons
Electrode	L 140, 1/16" diameter
Welding Current	300 amps DCRP
Voltage	24 volts
Deposition rate	10.0 lbs/hr
Operating factor	.40
Welding Man-hours	13,440
Electrical Power Consumed	59,566 KWH
Electrode required	26.1 tons
Shielding Gas required	268,800 ft ³
Labor and Overhead	\$25/ hr.
Electrical Power	\$.04125 per KWH
Filler Metal	\$7.36 per lb.
Shielding gas	\$.0696 per ft ³
Labor and Overhead costs	\$336,000
Electrical Power costs	\$2,457
Filler Metal costs	\$430,295
Shielding Gas costs	\$18,708
Total Costs	\$787,460

Table XXXVLaser Welding Parameters for HY-130

<u>Plate Thickness (in)</u>	<u>Beam Power (KW)</u>	<u>KW into Laser</u>	<u>Number of passes</u>	<u>Welding Speeds (IPM)</u>
3/4	12	140	1	30
1 1/4	12	140	2	30
1 1/2	12	140	2	30

Shielding gas - 200 CFH of Helium

purpose of this study, an operating factor of .70 was assumed. With this value of OF, the man-hours required were calculated to be 422. In turn, labor and overhead costs were determined to be \$10,550.

2. Electrical Power and Costs

The power requirements for obtaining 12 KW of beam power on the weld joint are in reality much higher, approximately 140 KW. The laser has an efficiency of 10% resulting in a beam output of 14 KW. Losses occurring with the external optics account for another 2 KW. Based on the 140 KW power requirements and 295.56 hours of beam time, approximately 41,378 KWH would be consumed. At \$.04125 per KWH, the cost of electricity was calculated to be \$1,707.

3. Shielding Gas and Costs

With a helium shielding gas flow rate of 200 CFH, 59,112 ft³ would be required for 295.56 hours of welding. The current cost of helium gas was determined to be \$.0942 per ft³ [46]. The cost of shielding gas was calculated to be \$5,568.

A summary of the factors considered in laser welding are presented in Table XXXVI.

H. Electron Beam Welding Process

Data on previously accomplished electron beam welding of HY-130 is presented in Table XXXVII. The 1" thick plate welding was completed by Coneybear [12]. Welding conditions for the 1/4" and 1/2" plate were taken from reference [40]. The EB welding conditions chosen for the economic analysis are shown in Table XXXVIII. Although EB guns with much higher power capabilities are available, 12 KW was chosen in order

to provide a comparison to the laser results. The welding speeds associated with the chosen EB parameters do not vary significantly with those for 12 KW of laser power. However, EB welding is accomplished in one welding pass for all the plate thicknesses encountered due to the greater penetration capabilities of the electron beam.

1. Welding Man-hours and Costs

Based on the welding speeds in Table XXXVIII, the 1.25" pressure hull would be welded at 26.6 in/min, the King frames at 21.8 in/min, and the normal frames at 37.9 in/min. The hours required to complete these weld joints were calculated to be 29.72 hours, 8.63 hours, and 182.3 hours respectively. The total welding hours were therefore calculated to be 220.65 hours. Again, these hours represent electron beam hours, the equivalent of arc hours for SMA or GMA welding.

Electron beam welding is a highly automated welding process. However, this author estimated that the operating factor for electron beam welding would be somewhat less than that used for laser welding due to the pump down time required to obtain the high vacuum required for electron beam welding. For the purpose of this analysis, an operating factor of .50 was assumed. With this OF, the man-hours required were calculated to be 441 hours. In turn, labor and overhead costs were determined to be \$11,025.

2. Electrical Power and Costs

This analysis assumed that the EB welding unit and power supplies had an electrical efficiency of 65%. Therefore, 18.5 KW of power would be required to obtain 12 KW of beam power. The total electrical power

Table XXXVISummary of Laser Welding Parameters and Costs

Linear feet of 2 pass welding	4,894 ft
Linear feet of 1 pass welding	34,546 ft
Laser input power	140 KW
Beam Power	12 KW
Welding speed	30 IPM
Operating factor	.70
Welding man-hours	422
Electrical power consumed	41,378 KWH
Shielding gas required	59,112 ft ³
Labor and overhead	\$25/hr
Electrical power	\$.04125 per KWH
Shielding gas	\$.0942 per ft ³
Labor and overhead costs	\$10,550
Electrical power costs	\$1,707
Shielding gas costs	\$5,568
Total costs	\$17,825

Table XXXVIIHY-130 Electron Beam Welding

<u>Thickness</u> <u>(in)</u>	<u>Beam power</u> <u>(KW)</u>	<u>Welding speed</u> <u>(IPM)</u>	<u>Heat Input</u> <u>(KJ/in)</u>
1/4	7.36	70	6/35
1/2	8 - 9.6	50	9.65 - 12.95
1	6.75	15	27

Table XXXVIIISelected EB Welding Parameters for HY-130

<u>Thickness (in)</u>	<u>Beam Power (KW)</u>	<u>Welding Speed (IPM)</u>	<u>Heat Input (KJ/in)</u>
3/4	12	37.9	19
1 1/4	12	26.6	27
1 1/2	12	21.8	33

Table XXXIXSummary of EB Welding Parameters and Costs

Linear feet of welding at 26.6 IPM	941 ft
Linear feet of welding at 21.8 IPM	3,953 ft
Linear feet of welding at 37.9 IPM	34,546 ft
EB input power	120 KW
Beam power	12 KW
Operating factor	.50
Welding Man-hours	441
Electrical power consumed	8,159 KWH
Labor and overhead	\$25/hr
Electrical power	\$.04125 per KWH
Labor and overhead costs	\$11,025
Electrical power costs	\$337
Total costs	\$11,362

consumed was calculated to be 8,159 KWH. At \$.04125 per KWH, the cost of electricity was in turn calculated to be \$337.

A summary of the factors considered in EB welding are presented in Table XXXIX.

I. Comparison of Welding Costs

Table XL shows a comparison of the calculated welding costs for the 4 welding processes considered in this analysis. The economic impacts of labor and filler metal costs as calculated for SMA and GMA processes are quite significant. A cost not considered in this analysis was equipment costs. These costs are very high for EB and laser, on the order of 450-500 million dollars. However, as can be seen from Table XL, the costs of filler metal alone for GMA and SMA is approaching the costs of laser or EB welding units. Also, this analysis was based on the need for depositing 24 tons of weld metal. An analysis for larger submarines, such as Trident, would undoubtedly result in even greater differences between SMA and GMA welding costs as compared to laser or EB.

Table XL

Comparison of Welding Parameters and Costs

<u>Item</u>	<u>SMA</u>	<u>GMA</u>	<u>Laser</u>	<u>EB</u>
Deposition Rate (lbs/hr)	3.0	10	-	-
Welding Speed (IPM)	6.0 - 6.4	11.5 - 12.3	30	21.8 - 37.9
Operating Factor	.30	.40	.70	.50
Welding Man-hours	59,734	13,440	422	441
Power Consumed (KWH)	103,398.4	59,566	41,378	8,159
Electrode Required (tons)	47.34	26.1	-	-
Labor and Overhead Costs	\$1,493,350	\$336,000	\$10,550	\$11,025
Electrical Power Costs	\$4,265	\$2,457	\$1,707	\$337
Filler Metal Costs	\$347,816	\$430,295	-	-
Shielding Gas Costs	-	18,708	5,568	-
Total Costs	\$1,845,431	\$787,460	\$17,825	\$11,362

CHAPTER VIII
RELIABILITY CONSIDERATIONS

Chapter VII established that significant potential exists for reductions in fabrications costs using laser or EB welding processes. However, economic consideration is but one aspect of the total impact. A welding process must also be capable of producing reliable welds. This aspect is crucial when dealing with critical structures such as submarines. The weld joint must possess adequate tensile properties, fracture resistance, hardness, etc. An assessment of these factors for SMA, GMA, EB, and laser welding of HY-130 was made by the Naval Research Laboratory [40]. Their investigations were made on 1/4" and 1/2" thick HY-130 plate. Tables XLI-XLV summarize their results. Both laser and EB welding processes appeared capable of producing satisfactory welds. Of particular note was the fracture toughness of the laser weldments. Laser weld joint fracture energy values were found to be 94.5 to 97.7 percent of those of the base plate.

Another aspect of reliability, and not covered in this study, is joint fitup. In the final analysis, it may turn out to be the most difficult factor to solve. Most laser and EB welding has been carried out with essentially zero gap fitup on relatively small specimens. The ability to provide the required close fitup tolerances for large structures, and to maintain the fitup while welding is yet to be proven. The ability to maintain the proper alignment of the welding beam with respect to the weld joint also needs to be assured.

With the relatively high welding speeds anticipated with laser or EB processes, improperly maintained welding parameters, even for a short period of time, could result in the entire weld being unsatisfactory.

Notwithstanding the above remarks, the advanced processes also possess the potential for increased reliability. Through the use of extensive automation, they could reduce the effects of the human factors involved such as worker attitude, fatigue, or other job related influences. Also, process controllers for laser welding already exists which are capable of precisely controlling the temperature of the work surface [47]. These controllers utilize an optical system which monitors the temperature of the work surface, and feeds the data back to the power control system to maintain a preset surface temperature. Therefore, increased reliability may be achieved through precise time and temperature control of the work surface heating.

Table XLI

Average Tensile Properties for 1/4" Thick Weldments

<u>Specimens</u>	<u>Fracture Location</u>	<u>0.2% YS (KSI)</u>	<u>UTS (KSI)</u>	<u>E (10⁶psi)</u>	<u>Hardness (RC)**</u>
Base metal	-	140.9	147.1	28.7	34.0
SMA Weld Joint	Weld Metal	115.9	144.6	29.2	33.5
GMA Weld Joint	Base Metal	147.5	147.9	30.2	37.5
EB Weld Joint	Base Metal	144.2	147.8	28.0	39.0
*LB Weld Joint	Base Metal	139.5	148.2	27.6	40.0

* Not preheated. Other weldments preheated to 248°F

** Weld metal values

YS - yield strength

UTS - ultimate strength

E - modulus of elasticity

Table XLII

Average Tensile Properties for 1/2" Thick Weldments

<u>Specimens</u>	<u>Fracture Location</u>	<u>0.2% YS (KSI)</u>	<u>UTS (KSI)</u>	<u>E (10⁶ psi)</u>	<u>Hardness ** (RC)</u>
Base metal	-	133.4	139.1	28.3	32.0
SMA Weld Joint	Weld Metal	117.7	136.9	28.7	29.0
GMA Weld Joint	Base Metal	132.9	138.6	28.1	34.0
EB Weld Joint	Base Metal	131.6	136.5	28.7	37.5
* LB Weld Joint	Base Metal	122.8	139.3	27.6	40.0

* not preheated. Other weldments preheated to 248°F

** Weld metal values

YS - yield strength

UTS - ultimate strength

E - modulus of elasticity

Table XLIII

Fracture Resistance Data of 1/4" Thick
HY-130 Weldments

<u>Specimens</u>	<u>DT Energy Range (ft-lb)</u>	<u>Average DT Energy Range (ft-lb)</u>
Base metal	342.0-415.0	391.0
SMA Weld Joint	293.0-358.0	334.0
GMA Weld Joint	264.0-305.0	285.0
EB Weld Joint	273.0-307.0	287.0
* LB Weld Joint	351.0-447.0	382.0

* Not preheated.

Table XLIVFracture Resistance Data of 1/2" Thick
HY-130 Weldments

<u>Specimens</u>	<u>DT Energy Range (ft-lb)</u>	<u>Average DT Energy Range (ft-lb)</u>
Base Metal	759.0-881.0	804.0
SMA Weld Joint	475.0-560.0	524.0
GMA Weld Joint	420.0-663.0	515.0
EB Weld Joint	536.0-739.0	662.0
* LB Weld Joint	567.0-948.0	760.0

* Not preheated

Table XLV

Fracture Resistance Assessment of 1/4" and 1/2"
Thick HY-130 Weldments

<u>Weld</u> <u>Joint</u>	<u>Percent Equivalence to Base Metal</u>	
	<u>1/4"</u>	<u>1/2"</u>
SMA	85.4	65.2
GMA	72.9	64.0
EB	73.4	82.3
* LB	97.7	94.5

* Not preheated

CHAPTER IX

CONCLUSIONS AND RECOMMENDATIONS

The results of the experimental work indicated that the potential exists for two pass welding of 1.5" thick HY-130 plate with 12-13KW of laser beam power, and at a welding speed of 30 inches per minute. The plots of temperature and strain data as measured during laser welding are qualitatively quite similar to that obtained for EB welding as conducted by Coneybear [12]. Unfortunately, the development of the multidimensional computer programs for predicting temperature changes and transient thermal strains occurring during welding had not progressed to completion in sufficient time for testing. Personnel involved with the computer program development estimate that it will be available for use early this summer. I recommend that initial testing of the program be accomplished based on the laser welding parameters and results outlined in this study. A unique factor supporting this recommendation is that the beam power on the work surface was measured. With other welding processes, including EB, an estimate of efficiency must be made to account for the power losses occurring between the power source and the work surface. Knowledge of the actual power transferred to the work surface eliminates a variable input to the computer program, and should provide for more accurate testing of the program.

The economic analysis comparing the four welding processes indicated that a significant potential exists for reducing fabrication costs using laser or EB. Although the absolute value of the cost figures arrived at might vary depending upon the investigator, assignment of operating

factors, or other considerations, it is the relative difference between the welding costs which is truly significant. Labor costs for SMA are much higher due to low weld metal deposition rates. Although labor costs are substantially reduced for GMA welding relative to SMA, the filler metal costs are higher. In fact, for both SMA and GMA, the cost of HY-130 filler metals alone are approaching the current cost estimates for a 15KW industrial CO₂ laser.

This author also gave some consideration to the relative merits of laser welding versus EB welding for submarine construction. When considering the thick pressure hull, the electron beam process initially appears ideal due to its deep single pass welding penetration capabilities. However, as determined in this study, thick pressure hull welding only accounted for a small percentage (10%) of the total welding considered. The remaining 90% of welding was comprised of frame construction and installation, using plate thicknesses substantially less than the pressure hull. Based on a discussion with Dr. Terai of M.I.T., EB welding does not appear suited to this welding requirement. The difficulty arises due to positioning problems with the EB gun in order to obtain a straight line of sight between the electron beam and the weld joint. Therefore, magnetic forces would have to be applied to curve the beam into the joint, complicating alignment procedures. In contrast, laser welding utilizes external optics which can direct the beam to inaccessible spots. Fillet welding is accomplished by directing the beam at a slight angle to the weld joint. The beam then tracks along the interface of the metal, completing a full penetration weld

in one or two passes, depending on the plate thicknesses involved. The laser welding process therefore appears more adaptable to submarine construction than the electron beam process. This author recommends that further experimental work be conducted with laser welding of HY-130 T joints to precisely determine penetration capabilities and distortion effects.

In summary, recommendations for further study include the following:

1. Compare the experimental results with predictions of a multi-dimensional computer analysis upon completion of the program development.
2. Conduct a residual stress analysis of the weldment.
3. Conduct a metallurgical characterization study of the weldment to complement the study by Stoop and Metzbower [40].
4. Conduct laser welding experiments with HY-130 T joints to determine welding parameters and distortion effects.

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APPENDIX A
TEMPERATURE AND STRAIN DATA

HY-130 SPECIMEN II
 TEMPERATURE .50" FROM WELD LINE
 WELDING PASS # 1

<u>Time</u> <u>(sec)</u>	<u>Temp.</u> <u>(°F)</u>	<u>Time</u> <u>(sec)</u>	<u>Temp.</u> <u>(°F)</u>	<u>Time</u> <u>(sec)</u>	<u>Temp.</u> <u>(°F)</u>
0	73	30	364	50	281
10	83	31	360	60	260
12	93	32	353	70	245
13	103	33	348	80	233
14	143	34	342	90	223
15	213	35	336	100	216
16	273	36	332	110	210
17	343	37	326	120	203
18	378	38	322	130	197
19	393	39	317	140	192
20	400	40	313	150	188
21	401	41	309	160	183
22	398	42	305	170	180
23	395	43	302	180	178
24	392	44	298	240	161
25	388	45	295	300	152
26	384	46	292	360	143
27	381	47	289	420	135
28	375	48	286		
29	371	49	283		

HY-130 SPECIMEN II
TEMPERATURE 1.25" FROM WELD LINE
WELDING PASS # 1

<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>	<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>	<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>
0	73	30	136	50	180
10	93	31	140	60	186
12	100	32	143	70	189
13	103	33	146	80	188
14	107	34	149	90	187
15	109	35	153	100	185
16	107	36	155	110	183
17	107	37	158	120	181
18	106	38	160	130	178
19	106	39	162	140	176
20	106	40	164	150	174
21	108	41	166	160	171
22	110	42	168	170	169
23	112	43	170	180	168
24	115	44	172	240	156
25	118	45	173	300	149
26	121	46	175	360	142
27	125	47	176	420	136
28	130	48	177		
29	133	49	178		

HY-130 SPECIMEN II
TEMPERATURE 2.25' FROM WELD LINE
WELDING PASS # 1

<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>	<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>	<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>
0	73	30	79	50	88
10	80	31	79	60	96
12	82	32	79	70	105
13	82	33	79	80	111
14	82	34	79	90	118
15	81	35	79	100	122
16	81	36	79	110	125
17	81	37	79	120	128
18	81	38	79	130	129
19	81	39	80	140	131
20	82	40	80	150	133
21	82	41	81	160	134
22	82	42	81	170	135
23	82	43	82	180	135
24	81	44	83	240	135
25	81	45	84	300	132
26	80	46	84	360	130
27	80	47	85	420	127
28	79	48	86		
29	79	49	87		

HY-130 SPECIMEN II
TEMPERATURE 4.25" FROM WELD LINE
WELDING PASS # 1

<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>	<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>	<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>
0	73	30	76	50	74
10	75	31	76	60	74
12	75	32	75	70	74
13	76	33	75	80	75
14	76	34	75	90	76
15	76	35	75	100	77
16	76	36	75	110	78
17	76	37	75	120	79
18	76	38	74	130	80
19	76	39	74	140	82
20	76	40	74	150	83
21	76	41	74	160	85
22	76	42	74	170	87
23	76	43	74	180	88
24	76	44	74	240	96
25	76	45	74	300	102
26	76	46	74	360	107
27	76	47	74	420	109
28	76	48	74		
29	76	49	74		

HY-130 SPECIMEN II
 TEMPERATURE .50" FROM WELD LINE
 WELDING PASS # 2

<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>	<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>	<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>
0	103	30	293	50	303
10	103	31	296	60	293
12	103	32	301	70	279
13	103	33	303	80	268
14	103	34	305	90	258
15	108	35	308	100	251
16	118	36	311	110	243
17	133	37	312	120	235
18	153	38	322	130	232
19	168	39	322	140	228
20	188	40	313	150	223
21	203	41	313	160	218
22	218	42	313	170	213
23	231	43	312	180	211
24	243	44	312	240	193
25	255	45	311	300	183
26	265	46	311	360	173
27	273	47	309	420	163
28	281	48	308		
29	288	49	306		

HY-130 SPECIMEN II
TEMPERATURE 1.25" FROM WELD LINE
WELDING PASS # 2

<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>	<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>	<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>
0	111	30	151	50	212
10	111	31	156	60	222
12	111	32	160	70	225
13	111	33	165	80	225
14	111	34	169	90	223
15	111	35	173	100	222
16	112	36	177	110	219
17	112	37	180	120	217
18	113	38	183	130	214
19	113	39	187	140	212
20	114	40	190	150	210
21	116	41	193	160	208
22	118	42	196	170	205
23	120	43	198	180	203
24	125	44	200	240	191
25	129	45	203	300	183
26	133	46	205	360	176
27	137	47	207	420	165
28	141	48	209		
29	146	49	211		

HY-130 SPECIMEN II
 TEMPERATURE 2.25" FROM WELD LINE
 WELDING PASS # 2

<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>	<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>	<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>
0	108	30	110	50	123
10	108	31	110	60	133
12	108	32	111	70	140
13	108	33	111	80	147
14	108	34	111	90	153
15	108	35	112	100	158
16	108	36	112	120	160
17	108	37	113	120	163
18	108	38	114	130	165
19	108	39	114	140	167
20	108	40	115	150	168
21	108	41	115	160	169
22	108	42	116	170	169
23	108	43	116	180	170
24	108	44	117	240	168
25	108	45	118	300	165
26	108	46	119	360	161
27	109	47	120	420	156
28	109	48	121		
29	109	49	122		

HY-130 SPECIMEN II
TEMPERATURE 4.25" FROM WELD LINE
WELDING PASS # 2

<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>	<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>	<u>Time</u> <u>(sec)</u>	<u>Temp</u> <u>(°F)</u>
0	109	30	109	50	109
10	109	31	109	60	109
12	109	32	109	70	109
13	109	33	109	80	109
14	109	34	109	90	111
15	109	35	109	100	112
16	109	36	109	110	113
17	109	37	109	120	114
18	109	38	109	130	115
19	109	39	109	140	117
20	109	40	109	150	118
21	109	41	109	160	119
22	109	42	109	170	121
23	109	43	109	180	123
24	109	44	109	240	129
25	109	45	109	300	135
26	109	46	109	360	138
27	109	47	109	420	142
28	109	48	109		
29	109	49	109		

HY-130 SPECIMEN II
 LONGITUDINAL STRAIN .50" FROM WELD LINE
 WELDING PASS #1

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
0	73	0	2.26	-2.26
10	83	-100	2.27	-102.27
12	93	- 75	.054	-75.05
13	103	-150	-4.11	-145.89
14	143	+ 75	-35.06	110.06
15	213	-600	-107.5	-492.50
16	273	-1250	-140.98	-1109.02
17	343	-1600	-92.48	-1507.52
18	378	-1750	-18.23	-1731.77
19	393	-1825	25.58	-1850.58
20	400	-1850	48.63	-1898.63
21	401	-1800	52.06	-1852.06
22	398	-1700	41.87	-1741.87
23	395	-1650	31.99	-1681.99
24	392	-1625	22.42	-1647.42
25	388	-1600	10.14	-1610.14
26	384	-1590	-1.61	-1588.39
27	381	-1590	-10.07	-1579.93
28	375	-1575	-26.10	-1548.90
29	371	-1560	-36.13	-1523.87
30	364	-1525	-52.48	-1472.52
31	360	-1500	-61.12	-1438.88
32	353	-1475	-75.08	-1399.92
33	348	-1450	-84.14	-1365.86
34	342	-1400	-94.06	-1305.94
35	336	-1375	-102.93	-1272.07
36	332	-1350	-108.29	-1241.71
37	326	-1300	-115.51	-1184.49
38	322	-1275	-119.79	-1155.21

HY-130 SPECIMEN II
 LONGITUDINAL STRAIN .50" FROM WELD LINE
 WELDING PASS #1
 (Cont'd.)

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measure strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
39	317	-1250	-124.55	-1125.45
40	313	-1225	-127.89	-1097.11
41	309	-1190	-130.84	-1059.16
42	305	-1150	-133.40	-1016.60
43	302	-1125	-135.07	-989.93
44	298	-1100	-136.97	-963.03
45	295	-1075	-138.16	-936.84
46	292	-1050	-139.14	-910.86
47	289	-1025	-139.93	-885.07
48	286	-1015	-140.53	-874.47
49	283	-1000	-140.53	-859.47
50	281	-975	-141.10	-833.90
60	260	-810	-138.24	-671.76
70	245	-700	-131.58	-568.42
80	233	-600	-123.21	-476.79
90	223	-500	-116.22	-383.78
100	216	-450	-110.21	-339.79
110	210	-400	-104.72	-295.28
120	203	-350	-97.96	-252.04
130	197	-300	-91.93	-208.07
140	192	-250	-86.76	-163.24
150	188	-225	-82.55	-142.45
160	183	-210	-77.23	-132.77
170	180	-200	-72.93	-127.07
180	178	-190	-71.85	-118.15
240	161	- 50	-53.54	3.54
300	152	10	-44.11	54.11
360	143	60	-35.06	95.06
420	135	100	-27.49	127.49

HY-130 SPECIMEN II
 LONGITUDINAL STRAIN 1.25" FROM WELD LINE
 WELDING PASS # 1

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
0	73	0	2.26	-2.26
10	93	70	.05	69.95
12	100	200	-2.67	202.67
13	103	210	-4.11	214.11
14	107	230	-6.26	236.26
15	109	305	-7.43	312.43
16	107	350	-6.26	356.26
17	107	370	-6.26	376.26
18	106	350	-5.7	355.70
19	106	320	-5.7	325.70
20	106	300	-5.7	305.70
21	108	280	-6.84	286.84
22	110	260	-8.04	268.04
23	112	240	-9.30	249.30
24	115	210	-11.30	221.30
25	118	170	-13.43	183.43
26	121	110	-15.67	125.67
27	125	55	-18.83	73.83
28	130	-5	-23.03	18.03
29	133	-30	-25.68	4.32
30	136	-90	-28.41	-61.59
31	140	-130	-32.16	-97.84
32	143	-170	-35.06	-134.94
33	146	-200	-38.02	-161.98
34	149	-230	-41.04	-188.96
35	153	-250	-45.14	-204.86
36	155	-280	-47.22	-232.78
37	158	-300	-50.37	-249.63
38	160	-320	-52.48	-267.52

HY-130 SPECIMEN II
LONGITUDINAL STRAIN 1.25" FROM WELD LINE
WELDING PASS # 1 (Cont'd)

162.

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
39	162	-340	-54.61	-285.39
40	164	-360	-56.75	-303.25
41	166	-370	-58.89	-311.11
42	168	-380	-61.05	-318.95
43	170	-390	-63.20	-326.80
44	172	-400	-65.37	-334.63
45	173	-410	-66.45	-343.55
46	175	-420	-68.61	-351.39
47	176	-430	-69.69	-360.31
48	177	-440	-70.77	-369.23
49	178	-445	-71.85	-373.15
50	180	-450	-74.0	-376.0
60	186	-490	-80.43	-409.57
70	189	-510	-83.61	-426.39
80	188	-500	-82.55	-417.45
90	187	-490	-81.49	-408.51
100	185	-475	-79.37	-395.63
110	183	-460	-77.23	-382.77
120	181	-440	-75.08	-364.92
130	178	-420	-71.85	-348.15
140	176	-410	-69.69	-340.31
150	174	-395	-67.53	-327.47
160	171	-380	-64.28	-315.72
170	169	-370	-62.13	-307.87
180	168	-350	-61.05	-288.95
240	156	-290	-48.26	-241.74
300	149	-250	-41.04	-208.96
360	142	-210	-34.09	-175.91
420	136	-180	-28.41	-151.59

HY-130 SPECIMEN II
 LONGITUDINAL STRAIN 2.25" FROM WELD LINE
 WELDING PASS # 1

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
0	73	0	2.26	-2.26
10	80	90	2.51	87.49
12	82	135	2.37	132.63
13	82	150	2.37	147.63
14	82	170	2.37	167.63
15	81	185	2.46	182.54
16	81	210	2.46	207.54
17	81	230	2.46	227.54
18	81	250	2.46	247.54
19	81	270	2.46	267.54
20	82	290	2.37	287.63
21	82	300	2.37	297.63
22	82	310	2.37	307.63
23	82	320	2.37	317.63
24	81	320	2.46	317.54
25	81	320	2.46	317.54
26	80	320	2.51	317.49
27	80	310	2.51	307.49
28	79	300	2.55	297.45
29	79	290	2.55	287.45
30	79	280	2.55	277.45
31	79	270	2.55	267.45
32	79	265	2.55	262.45
33	79	260	2.55	257.45
34	79	250	2.55	247.45
35	79	245	2.55	242.45
36	79	240	2.55	237.45
37	79	230	2.55	227.45
38	79	220	2.55	217.45

HY-130 SPECIMEN II
 LONGIDUTINAL STRAIN 2.25" FROM WELD LINE
 WELDING PASS # 1 (Cont'd)

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
39	80	215	2.51	212.49
40	80	210	2.51	207.49
41	81	200	2.46	197.54
42	81	195	2.46	192.54
43	82	185	2.37	182.63
44	83	180	2.27	177.73
45	84	170	2.14	167.86
46	84	165	2.14	162.86
47	85	160	1.99	158.01
48	86	150	1.82	148.18
49	87	145	1.63	143.37
50	88	140	1.42	138.58
60	96	70	-1.0	71.0
70	105	20	-5.15	25.15
80	111	-30	-8.66	-21.34
90	118	-80	-13.43	-66.57
100	122	-95	-16.44	-78.56
110	125	-120	-18.83	-101.17
120	128	-130	-21.32	-108.68
130	129	-140	-22.17	-117.83
140	131	-150	-23.91	-126.09
150	133	-160	-25.68	-134.32
160	134	-170	-26.58	-143.42
170	135	-180	-27.49	-152.51
180	135	-170	-27.49	-142.51
240	135	-170	-27.49	-142.51
300	132	-160	-24.79	-135.21
360	130	-150	-23.03	-126.97
420	127	-140	-24.48	-119.52

HY-130 SPECIMEN II
 LONGITUDINAL STRAIN .50" FROM WELD LINE
 WELDING PASS # 2

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
0	103	0	-4.11	4.11
10	103	-200	-4.11	-195.89
12	103	-300	-4.11	-295.89
13	103	-325	-4.11	-320.89
14	103	-300	-4.11	-295.89
15	108	0	-6.84	6.84
16	118	150	-13.43	163.43
17	133	175	-25.68	200.68
18	153	100	-45.14	145.14
19	168	0	-61.05	61.04
20	188	-100	-82.55	-17.45
21	203	-250	-97.96	-152.04
22	218	-375	-111.98	-263.02
23	231	-525	-122.48	-402.52
24	243	-700	-130.44	-569.56
25	255	-850	-136.41	-713.59
26	265	-925	-139.65	-785.35
27	273	-1025	-140.98	-884.02
28	281	-1070	-141.10	-928.90
29	288	-1100	-140.15	-959.85
30	293	-1125	-138.84	-986.16
31	296	-1125	-137.79	-987.21
32	301	-1125	-134.54	-989.42
33	303	-1120	-134.54	-985.46
34	305	-1110	-133.40	-976.60
35	308	-1100	-131.52	-968.48
36	311	-1100	-129.42	-970.58
37	312	-1090	-128.67	-961.33

HY-130 SPECIMEN II
 LONGITUDINAL STRAIN .50" FROM WELD LINE
 WELDING PASS # 2 (Cont'd)

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
38	322	-1090	-119.79	-970.21
39	322	-1090	-119.79	-970.21
40	313	-1085	-127.89	-957.11
41	213	-1080	-127.89	-952.11
42	313	-1080	-127.89	-952.11
43	312	-1075	-128.67	-946.33
44	312	-1060	-128.67	-931.33
45	311	-1050	-129.42	-920.58
46	311	-1040	-129.42	-910.58
47	309	-1025	-130.84	-894.16
48	308	-1010	-131.52	-874.48
49	306	-1000	-132.80	-867.20
50	303	- 990	-134.54	-855.46
60	293	- 890	-138.84	-751.16
70	279	- 775	-141.19	-633.81
80	268	- 690	-140.28	-549.72
90	258	- 600	-137.56	-462.44
100	251	- 550	-134.66	-415.34
110	243	- 500	-130.44	-369.56
120	235	- 450	-125.33	-324.67
130	232	- 400	-123.21	-276.79
140	228	- 350	-120.21	-229.79
150	223	- 325	-116.22	-208.78
160	218	- 300	-111.98	-188.02
170	213	- 275	-107.50	-167.50
180	211	- 250	-105.65	-144.35
240	193	- 150	087.80	-62.20
300	183	- 100	-77.23	-22.77
360	173	- 25	-66.45	41.45
420	163	25	-55.68	80.68

HY-130 SPECIMEN II
LONGITUDINAL STRAIN 1.25" FROM WELD LINE
WELDING PASS # 2

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction strain ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
0	111	0	-8.66	8.66
10	111	-125	-8.66	-116.34
12	111	-75	-8.66	-66.34
13	111	-15	-8.66	-6.34
14	111	-15	-8.66	-6.34
15	111	-25	-8.66	-16.34
16	112	75	-9.30	83.30
17	112	175	-9.30	184.30
18	113	225	-9.95	234.95
19	113	325	-9.95	334.95
20	114	360	-10.62	370.62
21	116	375	-11.99	386.99
22	118	375	-13.43	388.43
23	120	350	-14.91	364.91
24	125	325	-18.03	333.83
25	129	275	-22.17	297.17
26	133	225	-25.68	250.68
27	137	175	-29.33	204.33
28	141	125	-33.12	158.12
29	146	75	-38.02	113.02
30	151	50	-43.08	93.08
31	156	25	-48.26	63.26
32	160	0	-52.48	52.48
33	165	-15	-57.82	42.82
34	169	-25	-62.13	37.13
35	173	-60	-66.45	6.45
36	177	-75	-70.77	-4.23
37	180	-100	-74.0	-26.0
38	183	-120	-77.23	-42.77

HY-130 SPECIMEN II
 LONGITUDINAL STRAIN 1.25" FROM WELD LINE
 WELDING PASS # 2 (Cont'd)

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction strain ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
39	187	-135	-81.49	-53.51
40	190	-150	-84.66	-65.34
41	193	-175	-87.80	-87.20
42	196	-190	-90.90	-99.10
43	198	-200	-92.95	-107.05
44	200	-225	-94.97	-130.03
45	203	-235	-95.97	-139.03
46	205	-250	-99.93	-150.07
47	207	-265	-101.86	-163.14
48	209	-275	-103.72	-171.28
49	211	-285	-105.65	-179.35
50	212	-295	-106.58	-188.42
60	222	-360	-115.39	-244.61
70	225	-275	-117.85	-257.15
80	225	-375	-117.85	-257.15
90	223	-360	-116.22	-243.78
100	222	-345	-115.39	-229.61
110	219	-325	-112.85	-212.16
120	217	-310	-111.10	-198.90
130	214	-300	-108.41	-191.59
140	212	-285	-106.58	-178.42
150	210	-275	-104.72	-170.28
160	208	-250	-102.82	-147.18
170	205	-225	-99.93	-125.07
180	203	-220	-97.96	-122.04
240	191	-170	-85.71	-84.29
300	183	-150	-77.23	-72.77
360	176	-140	-69.69	-70.31
420	165	-125	-57.82	-67.18

HY-130 SPECIMEN II
 LONGITUDINAL STRAIN 2.25" FROM WELD LINE
 WELDING PASS # 2

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
0	108	0	-6.84	6.84
10	108	0	-6.84	6.84
12	108	30	-6.84	36.84
13	108	50	-6.84	56.84
14	108	50	-6.84	56.84
15	108	30	-6.84	36.84
16	108	50	-6.84	56.84
17	108	75	-6.84	81.84
18	108	100	-6.84	106.84
19	108	140	-6.84	146.84
20	108	175	-6.84	181.84
21	108	215	-6.84	221.84
22	108	230	-6.84	236.84
23	108	250	-6.84	256.84
24	108	270	-6.84	276.84
25	108	280	-6.84	286.84
26	108	290	-6.84	296.84
27	109	290	-7.43	297.43
28	109	290	-7.43	297.43
29	109	285	-7.43	292.43
30	110	290	-8.04	298.04
31	110	300	-8.04	308.04
32	111	310	-8.66	318.66
33	111	315	-8.66	323.66
34	111	320	-8.66	328.66
35	112	325	-9.30	334.30
36	112	325	-9.30	334.20
37	113	330	-9.95	339.95
38	114	330	-10.62	340.62

HY-130 SPECIMEN II
 LONGITUDINAL STRAIN 2.25" FROM WELD LINE
 WELDING PASS # 2 (Cont'd)

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
39	114	325	-10.62	335.62
40	115	325	-11.30	336.30
41	115	320	-11.30	331.30
42	116	315	-11.99	326.99
43	116	315	-11.99	321.99
44	117	305	-12.71	317.71
45	118	300	-13.43	313.43
46	119	290	-14.16	304.16
47	120	285	-14.91	299.91
48	121	280	-15.67	295.67
49	122	275	-16.44	291.44
50	123	270	-17.23	287.23
60	133	210	-25.68	235.68
70	140	125	-32.16	157.16
80	147	90	-39.02	129.02
90	153	65	-45.14	110.14
100	158	25	-50.37	75.37
110	160	0	-52.48	52.48
120	163	-10	-55.68	45.68
130	165	-25	-57.82	32.82
140	167	-40	-59.97	19.97
150	168	-50	-61.05	11.05
160	169	-60	-62.13	2.13
170	169	-70	-62.13	-7.87
180	170	-70	-63.70	-6.30
240	168	-15	-61.05	46.05
300	165	0	-57.82	57.82
360	161	10	-53.54	63.54
420	156	30	-48.26	78.26

HY-130 SPECIMEN II
TRANSVERSE STRAIN .50" FROM WELD LINE
WELDING PASS # 1

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
0	73	0	2.26	-2.26
10	83	-200	2.27	-202.27
12	93	-850	.05	-850.05
13	103	-1200	-4.11	-1195.89
14	143	-1475	-14.91	-1460.09
15	213	-600	-107.50	-492.50
16	273	300	-140.98	440.98
17	343	950	-92.48	1042.48
18	378	1350	-18.23	1368.23
19	393	1575	25.58	1549.42
20	400	1625	35.25	1589.75
21	401	1400	52.06	1347.94
22	398	1000	41.87	958.13
23	395	750	31.99	718.01
24	392	600	22.42	577.58
25	388	500	10.14	489.86
26	384	450	-1.61	451.61
27	381	425	-10.07	435.07
28	375	400	-26.10	426.10
29	371	390	-36.14	426.13
30	364	375	-52.48	427.48
31	360	370	-61.12	431.12
32	353	360	-75.08	435.08
33	348	350	-84.14	434.14
34	342	340	-94.06	434.06
35	336	325	-102.93	427.93
36	332	300	-108.29	408.29
37	326	275	-115.51	390.51
38	322	260	-119.79	379.79

HY-130 SPECIMEN II
 TRANSVERSE STRAIN .50" FROM WELD LINE
 WELDING PASS # 1 (Cont'd)

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
39	317	250	-124.55	374.55
40	313	225	-127.89	352.89
41	309	210	-130.84	340.84
42	305	200	-133.40	333.40
43	302	185	-135.07	320.07
44	298	175	-136.97	311.97
45	295	150	-138.16	288.16
46	292	140	-139.14	279.14
47	289	125	-139.93	264.93
48	286	115	-140.53	255.53
49	283	105	-140.53	245.53
50	281	100	-141.10	241.10
60	260	70	-138.24	208.24
70	245	25	-131.58	156.58
80	233	0	-123.21	123.21
90	223	0	-116.22	116.22
100	216	-10	-110.21	100.21
110	210	-10	-104.72	94.72
120	203	-10	- 97.96	87.96
130	197	-10	- 91.93	81.93
140	192	-10	- 86.76	76.76
150	188	-10	- 82.55	72.55
160	183	-10	- 77.23	67.23
170	180	-10	- 72.93	62.93
180	178	-10	- 71.85	61.85
240	161	-10	- 53.54	43.54
300	152	-10	- 44.11	34.11
360	143	0	- 35.06	25.06
420	135	0	- 27.49	17.49

HY-130 SPECIMEN II
TRANSVERSE STRAIN 1.25" FROM WELD LINE
WELDING PASS # 1

173.

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
0	73	0	2.26	-2.26
10	93	-200	.05	-200.05
12	98	-265	-1.80	-263.20
13	103	-75	-4.11	-70.89
14	107	50	-6.26	56.26
15	109	65	-7.43	72.43
16	107	50	-6.26	56.26
17	107	30	-6.26	36.26
18	106	-25	-5.70	-19.30
19	106	-75	-5.70	-69.30
20	106	-125	-5.70	-119.30
21	108	-225	-6.84	-218.16
22	110	-325	-8.04	-316.96
23	112	-400	-9.30	-390.70
24	115	-450	-11.30	-438.70
25	118	-460	-13.43	-446.57
26	121	-450	-15.67	-434.33
27	125	-435	-18.83	-416.17
28	130	-410	-23.03	-386.97
29	133	-400	-25.68	-374.32
30	136	-370	-28.41	-341.59
31	140	-325	-32.16	-292.84
32	143	-300	-35.06	-264.94
33	146	-270	-38.02	-231.98
34	149	-225	-41.04	-183.96
35	153	-215	-45.14	-169.86
36	155	-200	-47.22	-152.78
37	158	-185	-50.37	-134.63
38	160	-175	-52.48	-122.52

HY-130 SPECIMEN II
TRANSVERSE STRAIN 1.25" FROM WELD LINE
WELDING PASS # 1 (Cont'd)

174.

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
39	162	-165	-54.61	-110.39
40	164	-160	-56.75	-103.25
41	166	-150	-58.89	- 91.11
42	168	-140	-61.05	- 78.95
43	170	-130	-63.20	- 66.80
44	172	-125	-65.37	- 59.63
45	173	-120	-66.45	- 53.55
46	175	-115	-68.61	- 46.39
47	176	-110	-69.69	- 40.31
48	177	-105	-70.77	- 34.23
49	178	-100	-71.85	- 28.15
50	180	- 95	-74.00	21.00
60	186	- 65	-80.43	15.43
70	189	- 50	-83.61	33.61
80	188	- 40	-82.55	42.55
90	187	- 30	-81.49	51.49
100	185	- 28	-79.37	51.37
110	183	- 25	-77.23	52.23
120	181	- 25	-75.08	50.08
130	178	- 20	-71.85	51.85
140	176	- 15	-69.69	54.69
150	174	- 15	-67.53	52.53
160	171	- 15	-64.28	49.28
170	169	- 15	-62.13	47.13
180	168	- 10	-61.05	51.05
240	156	0	-48.26	48.26
300	149	0	-41.04	41.04
360	142	10	-34.09	44.09
420	136	20	-28.41	48.41

HY-130 SPECIMEN II
TRANSVERSE STRAIN 2.25" FROM WELD LINE
WELDING PASS # 1

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
0	73	0	2.26	-2.26
10	80	-115	2.51	-117.51
12	82	-75	2.37	-77.37
13	82	-25	2.37	-27.37
14	82	50	2.37	47.63
15	81	105	2.46	102.54
16	81	125	2.46	122.54
17	81	125	2.46	122.54
18	81	115	2.46	112.54
19	81	95	2.46	92.54
20	82	60	2.37	57.63
21	82	10	2.37	7.63
22	82	-45	2.37	-47.37
23	82	-100	2.37	-102.37
24	81	-165	2.46	-167.46
25	81	-175	2.46	-177.46
26	80	-190	2.51	-192.51
27	80	-195	2.51	-192.51
28	79	-210	2.55	-212.55
29	79	-200	2.55	-202.55
30	79	-195	2.55	-197.55
31	79	-190	2.55	-192.55
32	79	-185	2.55	-187.55
33	79	-160	2.55	-162.55
34	79	-170	2.55	-172.55
35	79	-165	2.55	-167.55
36	79	-160	2.55	-162.55
37	79	-155	2.55	-157.55
38	79	-155	2.55	-157.55

HY-130 SPECIMEN II
 TRANSVERSE STRAIN 2.25" FROM WELD LINE
 WELDING PASS # 1 (Cont'd)

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
39	80	-150	2.51	-152.51
40	80	-150	2.51	-152.51
41	81	-145	2.46	-147.46
42	81	-145	2.46	-147.46
43	82	-143	2.37	-145.37
44	83	-143	2.27	-145.27
45	84	-142	2.14	-144.14
46	84	-140	2.14	-142.14
47	85	-140	1.99	-141.99
48	86	-139	1.82	-140.82
49	87	-138	1.63	-139.63
50	88	-135	1.42	-136.42
60	96	-115	-1.00	-114.00
70	105	- 95	-5.15	- 89.85
80	111	- 75	-8.66	- 66.34
90	118	- 65	-13.43	- 51.57
100	122	- 55	-16.44	- 38.56
110	125	- 45	-18.83	- 26.17
120	128	- 40	-21.32	- 18.68
130	129	- 30	-22.17	- 7.83
140	131	- 25	-23.91	- 1.09
150	133	- 20	-25.68	5.68
160	134	- 15	-26.58	11.58
170	135	- 13	-27.49	14.49
180	135	- 5	-27.49	22.49
240	135	0	-27.49	27.49
300	132	15	-24.79	39.79
360	130	25	-23.03	48.03
420	127	35	-20.48	55.48

HY-130 SPECIMEN II
 TRANSVERSE STRAIN .50" FROM WELD LINE
 WELDING PASS # 2

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
0	103	0	-4.11	4.11
10	103	300	-4.11	304.11
12	103	500	-4.11	504.11
13	103	500	-4.11	504.11
14	103	350	-4.11	354.11
15	108	-100	-6.84	-93.16
16	118	-300	-13.43	-286.57
17	133	-300	-25.68	-274.32
18	153	-225	-45.14	-179.86
19	168	-100	-61.05	-38.95
20	188	0	-82.55	82.55
21	203	100	-97.96	197.96
22	218	190	-111.98	301.98
23	231	250	-122.48	372.48
24	243	325	-130.44	455.44
25	255	350	-136.41	486.41
26	265	400	-139.65	539.65
27	273	450	-140.98	590.98
28	281	475	-141.10	616.10
29	288	500	-140.15	640.15
30	293	515	-138.84	653.84
31	296	500	-137.79	637.79
32	301	500	-135.58	635.58
33	303	500	-134.56	634.56
34	305	490	-133.40	623.40
35	308	490	-131.52	621.52
36	311	490	-129.42	619.42
37	312	490	-128.67	618.67
38	322	490	-119.79	609.79

HY-130 SPECIMEN II
 TRANSVERSE STRAIN .50" FROM WELD LINE
 WELDING PASS # 2 (Cont'd.)

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
39	322	490	-119.79	609.79
40	313	490	-127.89	617.89
41	313	490	-127.89	617.89
42	313	490	-127.89	617.89
43	312	490	-128.67	618.67
44	312	490	-128.67	618.67
45	311	490	-129.42	619.42
46	311	480	-129.42	609.42
47	309	475	-130.84	605.84
48	308	470	-131.52	601.52
49	306	460	-132.80	592.80
50	303	450	-134.54	584.54
60	293	390	-138.84	528.84
70	279	350	-141.19	491.19
80	268	325	-140.28	465.28
90	258	290	-137.56	427.56
100	251	275	-134.66	409.66
110	243	260	-130.44	390.44
120	235	250	-125.33	375.33
130	232	250	-123.21	373.21
140	228	225	-120.21	345.21
150	223	225	-116.22	341.22
160	218	200	-111.98	311.98
170	213	200	-107.50	307.50
180	211	200	-105.65	305.65
240	193	225	- 87.80	312.80
300	183	225	- 77.23	302.23
360	173	230	- 66.45	296.45
420	163	250	- 55.68	305.68

HY-130 SPECIMEN II
TRANSVERSE STRAIN 1.25" FROM WELD LINE
WELDING PASS # 2

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
0	111	0	-8.66	8.66
10	111	180	-8.66	188.66
12	111	150	-8.66	158.66
13	111	75	-8.66	83.66
14	111	50	-8.66	58.66
15	111	0	-8.66	8.66
16	112	-175	-9.30	-165.70
17	112	-275	-9.30	-265.70
18	113	-450	-9.95	-440.05
19	113	-575	-9.95	-565.05
20	114	-675	-10.62	-664.38
21	116	-700	-11.99	-688.01
22	118	-725	-13.43	-711.57
23	120	-720	-14.91	-705.09
24	125	-675	-18.83	-656.17
25	129	-650	-22.17	-627.83
26	133	-600	-25.68	-574.32
27	137	-525	-29.33	-495.67
28	141	-490	-33.12	-456.88
29	146	-465	-38.02	-426.98
30	151	-450	-43.08	-406.92
31	156	-430	-48.26	-381.74
32	160	-425	-52.48	-372.52
33	165	-425	-57.82	-367.18
34	169	-425	-62.13	-362.87
35	173	-425	-66.45	-358.55
36	177	-425	-70.77	-354.23
37	180	-415	-74.00	-341.00
38	183	-405	-77.23	-327.77

HY-130 SPECIMEN II
TRANSVERSE STRAIN 1.25" FROM WELD LINE
WELDING PASS # 2 (Cont'd.)

180.

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Actual strain ($\mu\epsilon$)</u>
39	187	-400	-81.49	-318.51
40	190	-390	-84.66	-305.34
41	193	-380	-87.80	-292.20
42	196	-375	-90.90	-284.10
43	198	-365	-92.95	-272.05
44	200	-350	-94.97	-255.03
45	203	-335	-95.97	-239.03
46	205	-325	-99.93	-225.07
47	207	-325	-101.86	-223.14
48	209	-320	-103.72	-103.72
49	211	-315	-105.65	-105.65
50	212	-310	-106.58	-106.58
60	222	-275	-115.39	-115.39
70	225	-250	-117.85	-117.85
80	225	-230	-117.85	-117.85
90	223	-225	-116.22	-116.22
100	222	-225	-115.39	-115.39
110	219	-235	-112.84	-112.84
120	217	-235	-111.10	-111.10
130	214	-235	-108.41	-108.41
140	212	-235	-106.58	-106.58
150	210	-235	-104.72	-104.72
160	208	-235	-102.82	-102.82
170	205	-240	-99.92	-99.93
180	203	-240	-97.96	-97.96
240	191	-225	-85.71	-85.71
300	183	-215	-77.23	-77.23
360	176	-205	-69.69	-69.69
420	165	-195	-57.82	-57.82

HY-130 SPECIMEN II
 TRANSVERSE STRAIN 2.25" FROM WELD LINE
 WELDING PASS # 2

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Action strain ($\mu\epsilon$)</u>
0	108	0	-6.84	6.84
10	108	50	-6.84	56.84
12	108	0	-6.84	6.84
13	108	-10	-6.84	-3.16
14	108	-15	-6.84	-8.16
15	108	-15	-6.84	-8.16
16	108	-20	-6.84	-13.16
17	108	-65	-6.84	-58.16
18	108	-100	-6.84	-93.16
19	108	-150	-6.84	-143.16
20	108	-200	-6.84	-193.16
21	108	-240	-6.84	-233.16
22	108	-260	-6.84	-253.16
23	108	-275	-6.84	-268.16
24	108	-275	-6.84	-268.16
25	108	-275	-6.84	-268.16
26	108	-260	-6.84	-253.16
27	109	-250	-7.43	-242.57
28	109	-240	-7.43	-232.57
29	109	-240	-7.43	-232.57
30	110	-235	-8.04	-226.96
31	110	-240	-8.04	-231.96
32	111	-245	-8.66	-236.34
33	111	-250	-8.66	-241.34
34	111	-260	-8.66	-251.34
35	112	-275	-9.30	-265.70
36	112	-285	-9.30	-275.70
37	113	-300	-9.95	-290.05
38	114	-300	-10.62	-289.38

HY-130 SPECIMEN II
 TRANSVERSE STRAIN 2.25" FROM WELD LINE
 WELDING PASS # 2 (Cont'd.)

<u>Time (sec)</u>	<u>Temp (°F)</u>	<u>Measured strain ($\mu\epsilon$)</u>	<u>Correction factor ($\mu\epsilon$)</u>	<u>Action strain ($\mu\epsilon$)</u>
39	114	-300	-10.62	-289.38
40	115	-300	-11.30	-288.70
41	115	-300	-11.30	-288.70
42	116	-300	-11.99	-288.01
43	116	-300	-11.99	-288.01
44	117	-300	-12.71	-287.29
45	118	-300	-13.43	-286.57
46	119	-300	-14.16	-285.84
47	120	-300	-14.91	-285.09
48	121	-300	-15.67	-284.33
49	122	-300	-16.55	-283.56
50	123	-300	-17.33	-282.67
60	133	-290	-25.68	-264.32
70	140	-260	-32.16	-227.84
80	147	-240	-39.02	-200.98
90	153	-230	-45.14	-184.86
100	158	-220	-50.37	-169.63
110	160	-210	-52.48	-157.52
120	163	-200	-55.68	-144.32
130	165	-200	-57.82	-142.18
140	167	-190	-59.97	-130.03
150	168	-190	-61.05	-128.95
160	169	-180	-62.13	-117.87
170	170	-180	-62.13	-117.87
180	168	-180	-63.20	-116.80
240	165	-170	-61.05	-108.95
300	161	-160	-57.82	-102.18
360	156	-150	-53.54	- 96.46
420		-130	-48.26	- 81.74

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